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THESIS

TROPICAL CYCLONE MOTION AND RECURVATURE IN TCM-90

Submitted by

Michael E. Fitzpatrick

Department of Atmospheric Science

In partial fulfillment of the requirements

for the degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer, 1992

COLORADO STATE UNIVERSITY

May 14, 1992

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY MICHAEL E. FITZPATRICK ENTITLED TROPICAL CYCLONE MOTION AND RECURVATURE IN TCM-90 BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

TROPICAL CYCLONE MOTION AND RECURVATURE IN TCM-90

Rawinsonde and satellite data collected during the Tropical Cyclone Motion (TCM-90) experiment, which was conducted during the summer of 1990 in the Western North Pacific, is used to examine tropical cyclone steering motion and recurvature. TCM-90 composite results are compared with those found in a composite study using twenty-one years (1957-77) of Western North Pacific rawinsonde data during the same August–September period and also for all months during this same 21-year period.

Both data sets indicate that the composite deep-layer-mean (850-300 mb) winds 5-7° from the cyclone center provide an important component of the steering flow for tropical cyclones. However, despite the rawinsonde data enhancements of the TCM-90 experiment, data limitations prevented an accurate observation of steering flow conditions at individual time periods or for the average of only 5-10 time periods when composited together.

Examination of environmental wind fields surrounding a recurving cyclone (Typhoon Flo, Sept. 1990), and those for non-recurving TCM-90 storms verify significant differences in the upper tropospheric zonal wind fields north and northwest of the tropical cyclone one to two days prior to the beginning of the initial right turn of recurvature. Flo actually began to recurve when 200 mb positive zonal winds had penetrated to within 6 degrees radius of the cyclones' center in the northwest. Tropical cyclones which did not recurve had negative zonal winds at this radius and azimuth. This special area to the north and northwest of the cyclone has been termed the "window of forecast opportunity".

Basic statistical analyses of the typical spread of individual wind values at specific octants and 2 degree radial belts were made for all TCM-90 rawinsonde and satellite wind

data composites. The typical standard deviation about the mean of composited zonal and meridional winds in individual octants and radial belts was 5-6 m/s at lower levels and 6-7 m/s at upper levels. Zonal wind differences in excess of this threshold would be required for confidence in distinguishing between individual cases of recurvature and non-recurvature.

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The author is appreciative of the opportunities he has had to learn of tropical cyclones first hand through aircraft reconnaissance experience on Guam and from duty as a reconnaissance flight coordinator at the National Hurricane Center in Miami.

And, special thanks are extended to Connie for her love and understanding during this long process.

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LIST OF SYMBOLS, ACRONYMS AND DEFINITIONS

Best Track = A subjectively smoothed path, versus a precise and very erratic fix-to-fix path, used to represent the estimated best known movement of a tropical cyclone.

BMRC = (Australian) Bureau of Meteorology Research Centre

CSU = Colorado State University

GMS = (Japanese) Geostationary Meteorological Satellite

IOP = Intensive Observing Period

HRD = Hurricane Research Division

JTWC = Joint Typhoon Warning Center, Guam

mb = millibar

NAT = Natural Coordinate system-with respect to N-S-E-W geographical reference.

NCAR = National Center for Atmospheric Research

NOAA = National Oceanic and Atmospheric Administration

OCT = Octant

ODW = Omega dropwindsonde

n mi = nautical mile

NR = Non-recurving cyclones

R = Recurving cyclones

R point = The location where a recurving cyclone first begins to deviate from its previous west-northwest course.

Rawinsonde = Instrument used to measure the vertical profile of atmospheric temperature, relative humidity, pressure and winds. It is carried aloft by balloon and data are transmitted over radio frequencies to the receiving location.

Recurvature = The turning of a tropical cyclone from an initial path toward the west and poleward to east and poleward.

ROT = Coordinate system oriented with respect to the cyclone direction of motion.

S.D. = Standard Deviation

SPECTRUM = SPecial Experiment Concerning Typhoon Recurvature and Unusual Motion.

TATEX = Taiwan Area Typhoon EXperiment.

TC = Tropical Cyclone

TS = Tropical Storm

TCM-90 = Tropical Cyclone Motion 1990 field experiment

WMO = World Meteorological Organization

WNP = Western North Pacific

Chapter 1

INTRODUCTION

1.1 Tropical Cyclone Motion

Forecasting the movement of tropical cyclones is one of the most challenging problems in tropical meteorology. Although many attempts at objectively predicting cyclone motion have been made using statistical and dynamical methods, forecasts for specific tropical cyclones remain highly uncertain. The determination of whether a cyclone will move on a westerly course or recurve to the north or northeast typically results in large forecast errors. This is shown in the typical position error statistics (Fig. 1.1) published by the Joint Typhoon Warning Center (JTWC, 1990). Using the 1989 tropical cyclone season, a typical mean forecast position error for a 24 hour forecast is about 120 n mi. The largest forecast errors are generally associated with an incorrect assessment of the recurvature situation. Errors of 1850 km (1000 n mi) or more at the 72 hour forecast point may occur in these cases (Elsberry, 1988). These errors can have a devastating impact if the storm is approaching a heavily populated coastline. If a landfall forecast is made but the cyclone recurves, millions of dollars are lost on unnecessary evacuation and preparations. On the other hand, if the cyclone is predicted to recurve away from the coast, but does not, the loss of lives and property can be tremendous. It is estimated that the cost of preparing a 450 km stretch of U.S. Gulf Coast for a hurricane to be about 50 million dollars (Sheets, 1990).

Position errors can usually be attributed to (1) poor initial storm motion estimates or (2) poor steering flow wind observations and forecasts. Individual tropical cyclones often behave somewhat erratically. There are several obvious reasons why cyclones can move erratically over a short period of time. (1) Apparent changes in motion are due

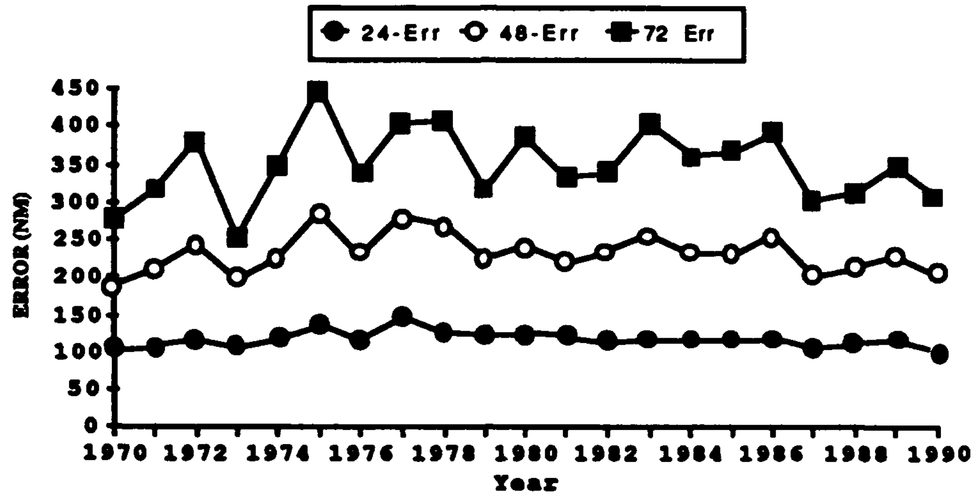


Figure 1.1: The forecast errors for the positions of Northwest Pacific storms from 1970-1990. From the 1990 Annual Tropical Cyclone Report.

measurement errors. Various position-fixing techniques such as by satellite, aircraft, or radar have characteristic reliabilities. The accuracy of an individual measurement depends upon the instrument system used in determining position and on the stage of development of the storm. (2) Actual changes in the tropical cyclone's motion can occur due to internal or external influences. A subjective after-the-fact estimate of storm track is available and is called the "best track". These position estimates weigh the relative merits of cyclone center fixes and determine the most likely position of a storm at six-hour intervals. The best track positions are assumed to be the storm position data with the least amount of overall position scatter. Figure 1.2 shows the very large variation in storm motion that can occur during a season. In particular, note that Typhoon Orchid had three periods where the direction of movement varied through 360 degrees in a short period of time.

1.2 TCM-90 Project

Many researchers have examined the relationship of tropical cyclone movement to surrounding flow. But surrounding cyclone data sources are always very limited. However, during August and September 1990, four separate but concurrent field experiments were conducted over the Western North Pacific (WNP) to study the motion of tropical

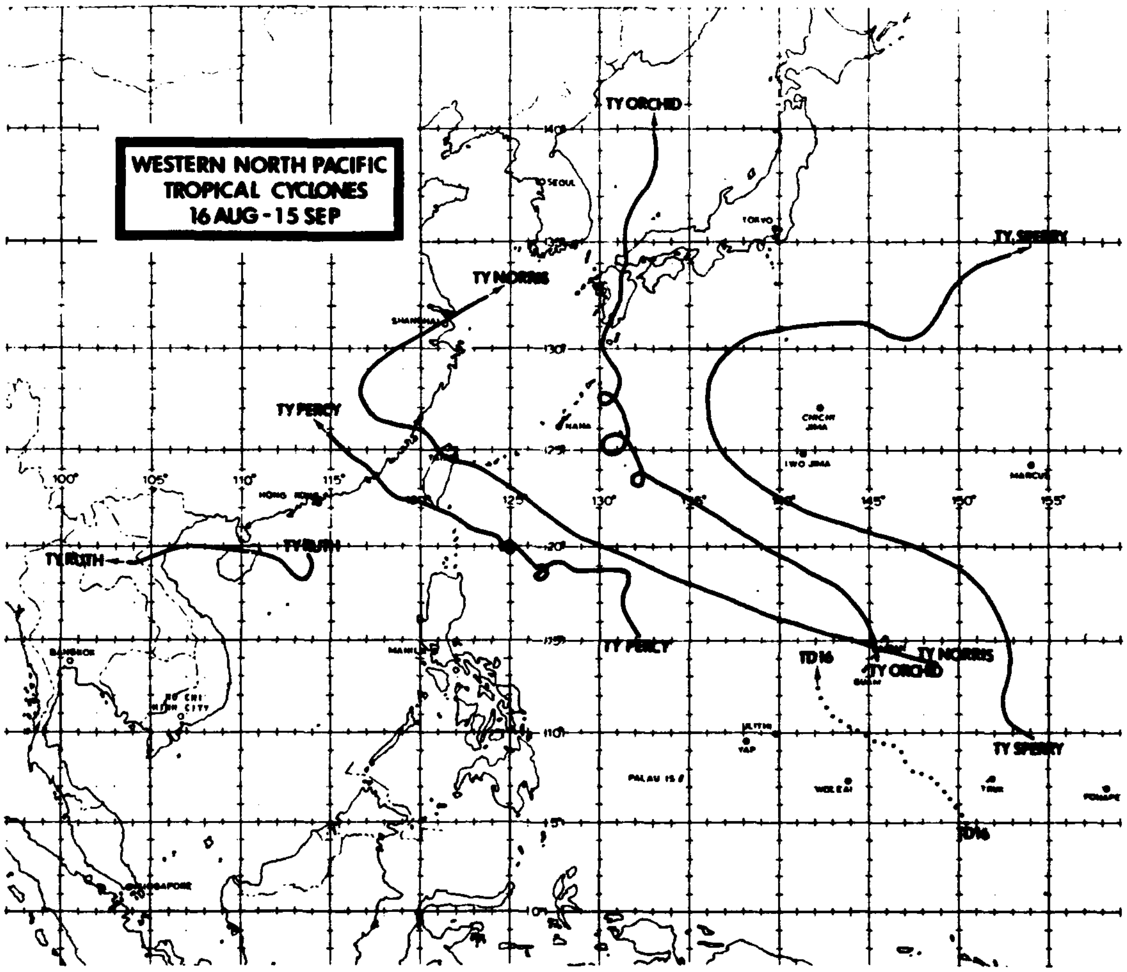


Figure 1.2: 1980 Best track positions of Northwest Pacific storms. From the 1980 Annual Tropical Cyclone Report.

cyclones. These included the Tropical Cyclone Motion Experiment of the US Navy (TCM-90), TYPHOON-90, a combined atmospheric-oceanographic experiment conducted by the USSR, the SPECTRUM (Special Experiment Concerning Typhoon Recurvature and Unusual Motion) project of the Typhoon Committee of the Economic and Social Commission for Asia and the Pacific (ESCAP), which is part of the World Meteorological Organization (WMO), and a fourth experiment organized by the Taiwan Central Weather Bureau called TATEX (Taiwan Area Typhoon Experiment).

The TCM-90 field experiment was the culmination of a five-year Tropical Cyclone research initiative of the Office of Naval Research Marine Meteorology Program. TCM-90 was specially designed to study tropical cyclone motion. The aims of the experiment were to obtain an enhanced observational data set that could be used to test hypotheses on the mechanisms of tropical cyclone motion. This observational network of the Western North Pacific represented a unique opportunity to quantitatively study individual case and time period tropical cyclone steering flow currents. Special data collection efforts were made, especially during 17 days which were designated as Intensive Observing Periods (IOPs) during which rawinsondes were launched at 6-hourly intervals and other observation platforms increased their data coverage. The rawinsonde observations were taken at regular WMO stations as well as at special sites and weather ships. These special observations, particularly the extra ship rawinsonde observations, provided the best opportunity yet to measure surrounding cyclone individual case steering flow. In addition, satellite-derived cloud-drift winds were provided during a number of the IOPs studied. For further details on the TCM-90 experiment, refer to Elsberry *et al.* (1990).

1.3 Summary of Objectives

A major feature of the TCM-90 field experiment was to determine if the rawinsonde augmentation employed together with the special satellite techniques would be able to give significantly improved individual case and time period surrounding cyclone steering information so as to improve cyclone motion understanding and forecasting. This study uses the enhanced data base gathered during the TCM-90 project and examines several aspects of tropical cyclone motion:

1. A data compositing scheme is used to compare a 21-year WNP rawinsonde data base to that gathered during TCM-90. Deep-layer-mean (850-300mb) wind flow vectors found at various radii relative to the tropical cyclone center positions are analyzed. This information is examined to try to determine a representative steering flow for cyclone motion and for any possible forecast clues that might be used operationally.

2. The typical variability of individual rawinsonde data is examined to determine the extent to which individual time period steering currents can be determined. Reasons for individual case variations are discussed.

3. A comparison is made of the environmental wind field differences between Typhoon Flo, a storm that recurved to the northeast, and those storms that maintained a west-northwesterly track throughout their entire life cycles. Critical levels and locations for zonal wind differences are determined and their temporal relationship to storm recurvature is investigated.

Chapter 2

RAWINSONDE COMPOSITING AND DATA ANALYSIS PROCEDURES

2.1 Rawinsonde Compositing Philosophy

Tropical cyclones spend most of their lifetimes over data sparse oceanic areas. Due to the scarcity of oceanic rawinsonde data, representative information on the characteristics of surrounding flow patterns of individual tropical cyclones is usually very deficient. However, by compositing the available rawinsonde soundings from many cyclones with similar motion characteristics over many parts of the ocean, many of the data limitations can be overcome and the basic physical processes and relationships involved with the tropical cyclone motion process better understood.

Compositing procedures smooth out features particular to an individual tropical cyclone. The value of composites lies in the large number of observations whose averaging together acts to smooth out the always present small scale natural wind variation and the sometimes present random instrumental inconsistencies. Large numbers of observations will counteract the natural and instrumental inconsistencies of individual soundings. The resulting composite averages should reveal characteristics common to all cyclones in a given stratification and allow for quantitative analysis of these features. A more detailed description of compositing philosophy can be found in Williams and Gray (1973), Frank (1977), Gray (1981), and other Colorado State University tropical cyclone research reports.

2.2 Rawinsonde Compositing Procedures

This study has used composites based on 21 years (1957-77) of Western North Pacific rawinsonde data and on two months (Aug-Sept, 1990) of TCM-90 rawinsonde data from

the same geographic area. The rawinsonde data comprising the 21 year data set are taken from the Asheville US Climatic Center data tapes, the National Center for Atmospheric Research (NCAR), and from Japanese and East Asian upper air soundings. The TCM-90 data set draws from all available land based and ship based rawinsonde soundings taken during the experiment. This includes data taken at both regular and special locations and times. Comparisons of experiment data are made with the extensive additional data from previous year measurements. Figure 2.1 shows the rawinsonde data network for the TCM-90 project.

The rawinsonde compositing techniques used with this study display data on a 15° circular radius grid. All rawinsondes were composited into a cylindrical coordinate system centered on the cyclones' best track positions. Soundings taken within 15° latitude radius of a tropical cyclone were used in the compositing grid shown in Fig. 2.2. The grid consists of eight radial bands extending from 0-1, 1-3, 3-5, 5-7, 7-9, 9-11, 11-13, and 13-15° from the tropical cyclone center. The grid also has eight octants of 45° extent that display data in various azimuthal directions and 23 vertical pressure levels from the surface up to 50 mb.

Two different reference frames are used. The first is the unchanged Natural or NAT coordinate system. It composites data with respect to the instantaneously fixed cyclone center in a N-S-E-W or geographical coordinate system. One of the averaged parameters available in this system is the zonal wind component, and this will be used extensively in Chapters 4 and 5.

The second reference frame involved is the Rotated or (ROT) coordinate system, which composites data with respect to the instantaneously fixed cyclone center and the direction to where the storm is moving. Each wind vector observation is resolved into a parallel component along the direction of cyclone movement and a component normal to the direction as shown in Fig. 2.3. In Chapter 3 these components are used to examine the relationship of the environmental winds to the actual cyclone motion.

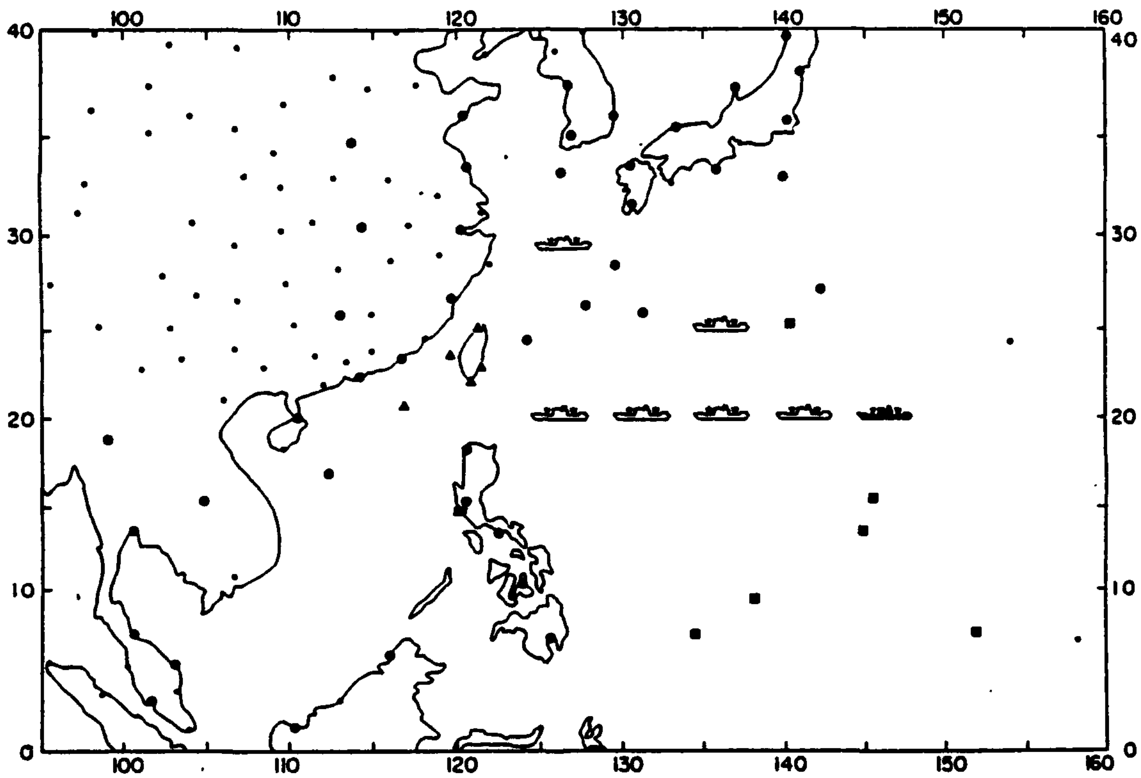


Figure 2.1: Upper-air network for TCM-90 and concurrent experiments. Regular rawinsonde stations with 12-hourly soundings are indicated by small circles. The large circles, squares, and triangles represent the special rawinsonde stations at 06 and 18 UTC for SPECTRUM, U.S. and Taiwan stations, respectively. The ship symbols show the fixed positions of the participating ships. (Elsberry *et al.*, 1990).

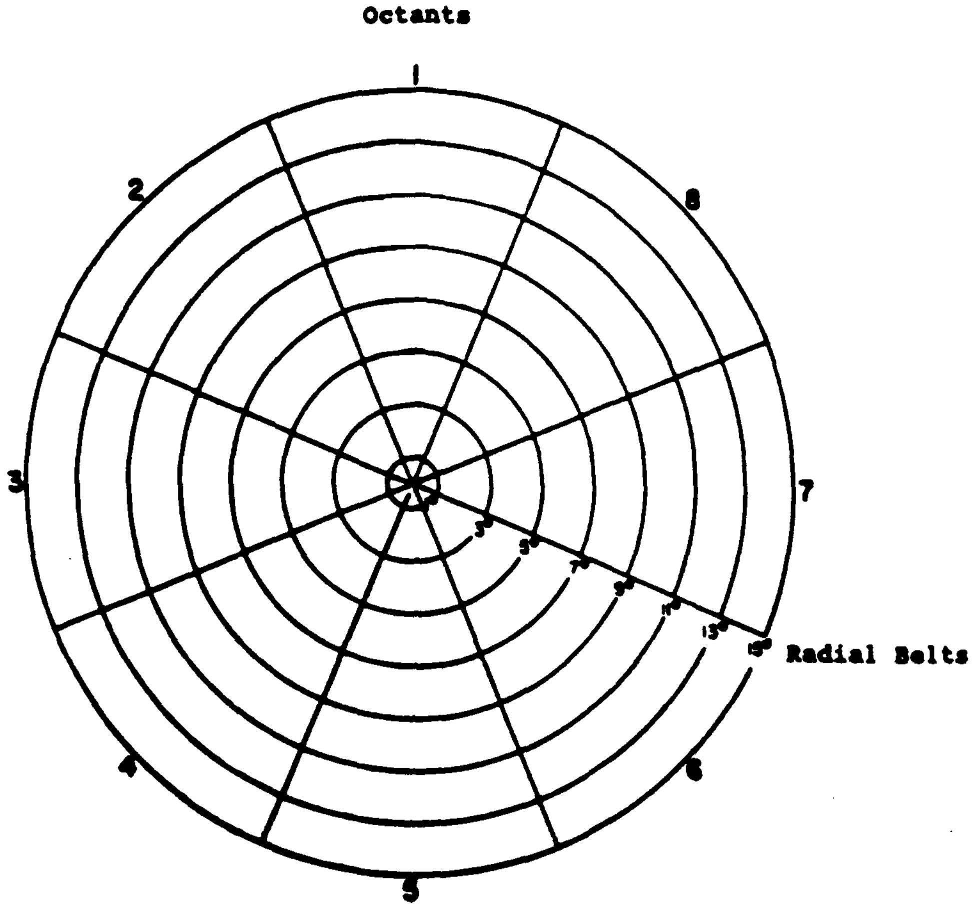


Figure 2.2: Grid used for compositing rawinsonde data. Note the eight azimuthal octants and eight radial belts used in the compositing system. (Chan and Gray, 1982).

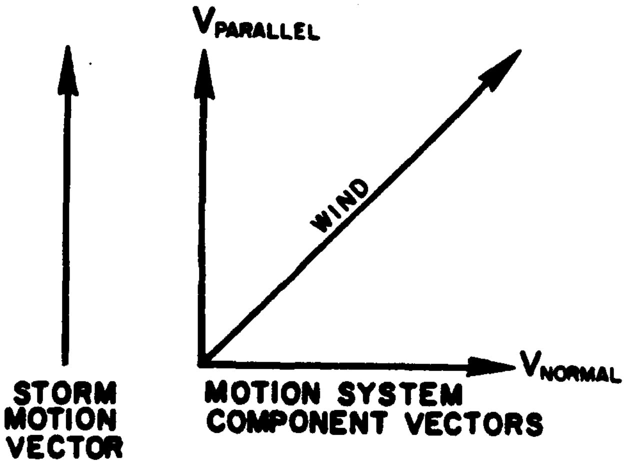


Figure 2.3: Parallel and perpendicular components of a wind vector showing their relation to the storm motion vector. (Chan and Gray, 1982).

2.3 Cyclone Track Stratifications

This motion study analyzes two types of cyclone tracks: recurving cyclones and non-recurving cyclones. Figure 2.4 shows the typical track of these two basic types of cyclones. The Joint Typhoon Warning Center (JTWC, 1988), defines tropical cyclone recurvature as "The turning of a tropical cyclone from an initial path west and poleward to east and poleward". Figure 2.5 illustrates this definition. In this motion study, the location where recurving cyclones first begin to turn to the right from their previous west-northwesterly track is of primary importance. This is taken to be the point of initial recurvature and is designated the "R-point" (Hodanish, 1991), and is shown in Fig. 2.6.

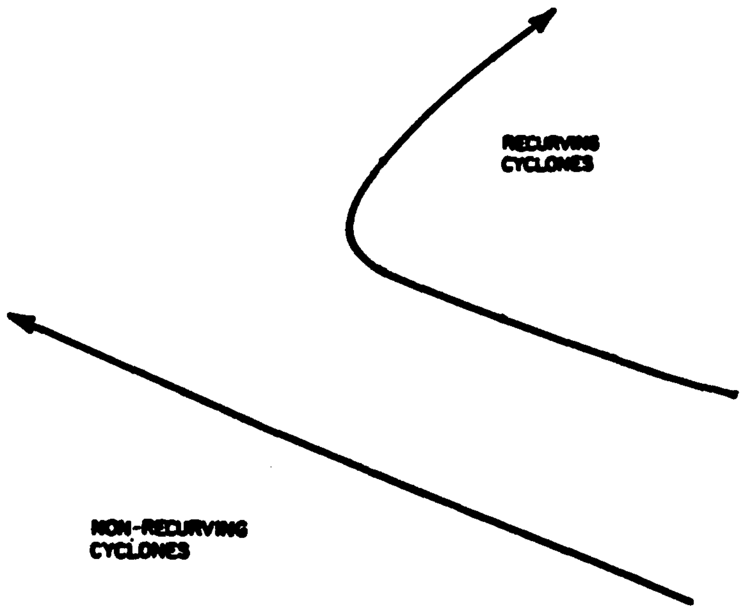


Figure 2.4: Typical tracks of the cyclones analyzed in this study.

Recurving cyclones (R) in this study are defined as those which change direction a minimum of 45° to the right of their previous west-northwest course within 36 hours after passing the R-point. The cyclone must also have undergone recurvature (by JTWC definition) within 48 hours after passing the R-point. In addition, recurving cyclones must move on a course between 260° and 330° for a minimum of 24 hours prior to reaching the

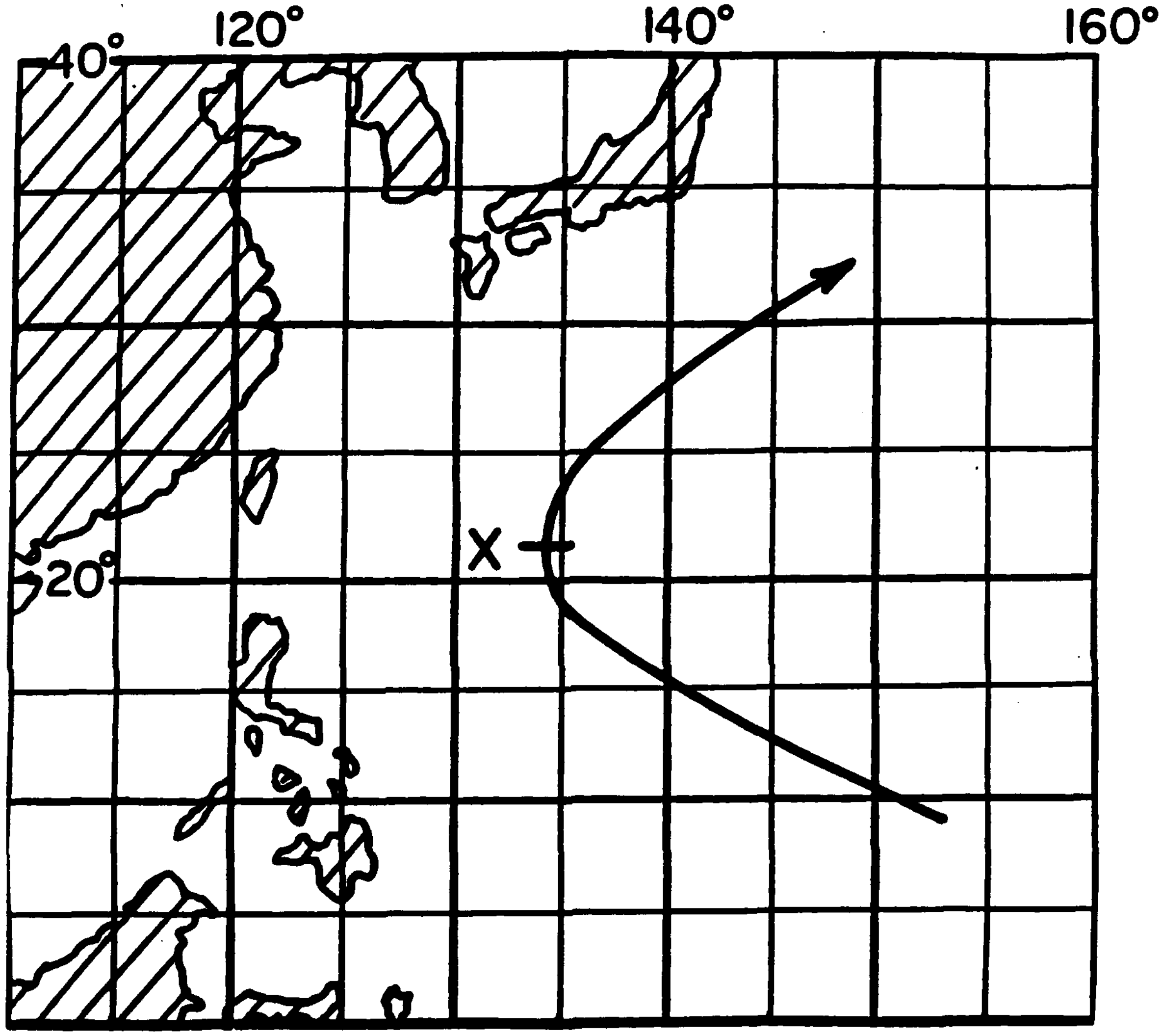


Figure 2.5: A typical recurving cyclone track. According to JTWC (1988), a cyclone undergoes recurvature when the cyclone first takes on an eastward component of motion (shown here by the letter "X"). (JTWC, 1988)

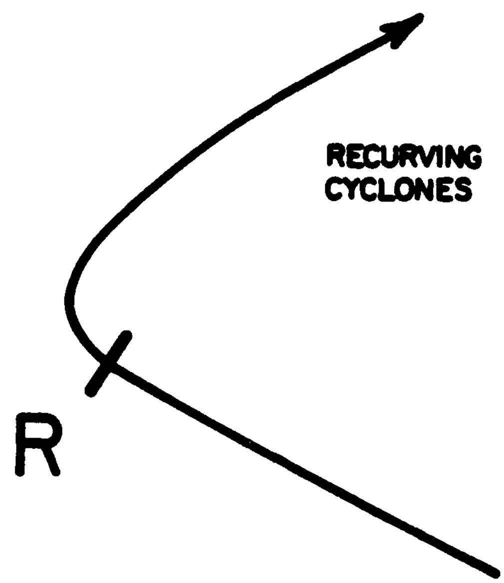


Figure 2.6: Track of recurving cyclone, where the "R" represents the R-point as used in this study. This is the location where the recurving cyclone first begins to turn to the right from their west-northwest track. (Hodanish, 1991)

R-point. This last restriction allows for the observation of any changes which may occur in the wind fields prior to the beginning of recurvature (Hodanish, 1991).

Non-recurving (NR) cyclones are defined here as cyclones which tracked between 260° and 330° throughout their lifetime. In addition to the recurving and non-recurving cyclones, three additional cyclone stratifications were made according to the general direction of motion, i.e., West, North, and Northeast. These are examined in Chapter 3. Tracks of the 13 TCM-90 cyclones are found in the Appendix.

2.4 Cyclone Time Periods

Temporal changes of the environmental wind fields surrounding the cyclones are observed by dividing the recurving tracks into five consecutive 24-hour time segments. (See Fig. 2.7). Time is measured with respect to the R-point. This procedure facilitates the examination of how synoptic scale wind fields interacted with the cyclone circulation prior to and after recurvature. The first three time periods, R0, R1, and R2 occur as the cyclones were moving on a west-northwest course before the cyclone reaches the R-point,

while the fourth and fifth time periods, R3 and R4, occurred after the cyclone has passed the R-point.

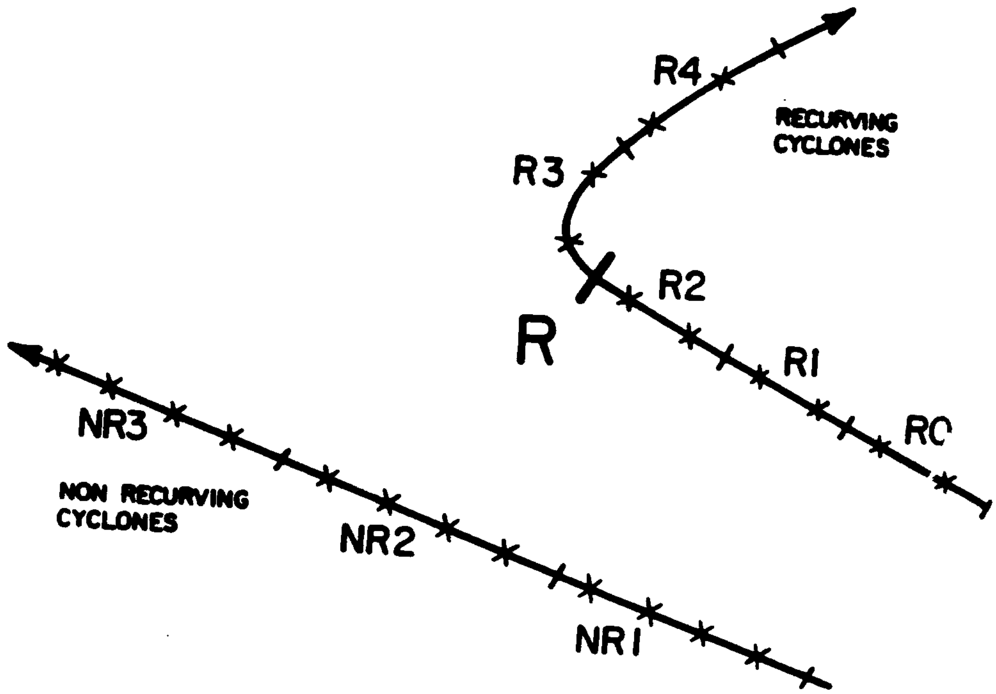


Figure 2.7: The TCM-90 recurving (R0 through R4) and non-recurving (NR1-NR3) cyclone tracks divided up into individual time periods. Table 2.1 and Fig. 2.8 summarize individual characteristics of each time period. The X characters represent 12-hour time steps.

Non-recurving cyclone tracks were divided into three equal time periods since no track reference (equivalent to the R-point) was designated. The average length of each NR period was 42 hours for the TCM-90 cyclones. Figure 2.7 shows a typical non-recurving track divided up into three time periods. Figure 2.8 summarizes the mean track speed and direction information for TCM-90 recurving and non-recurving cyclones. Table 2.1 gives the same information in a different format and adds information on Typhoon Flo, a recurving storm from TCM-90 that is closely examined in Chapter 4.

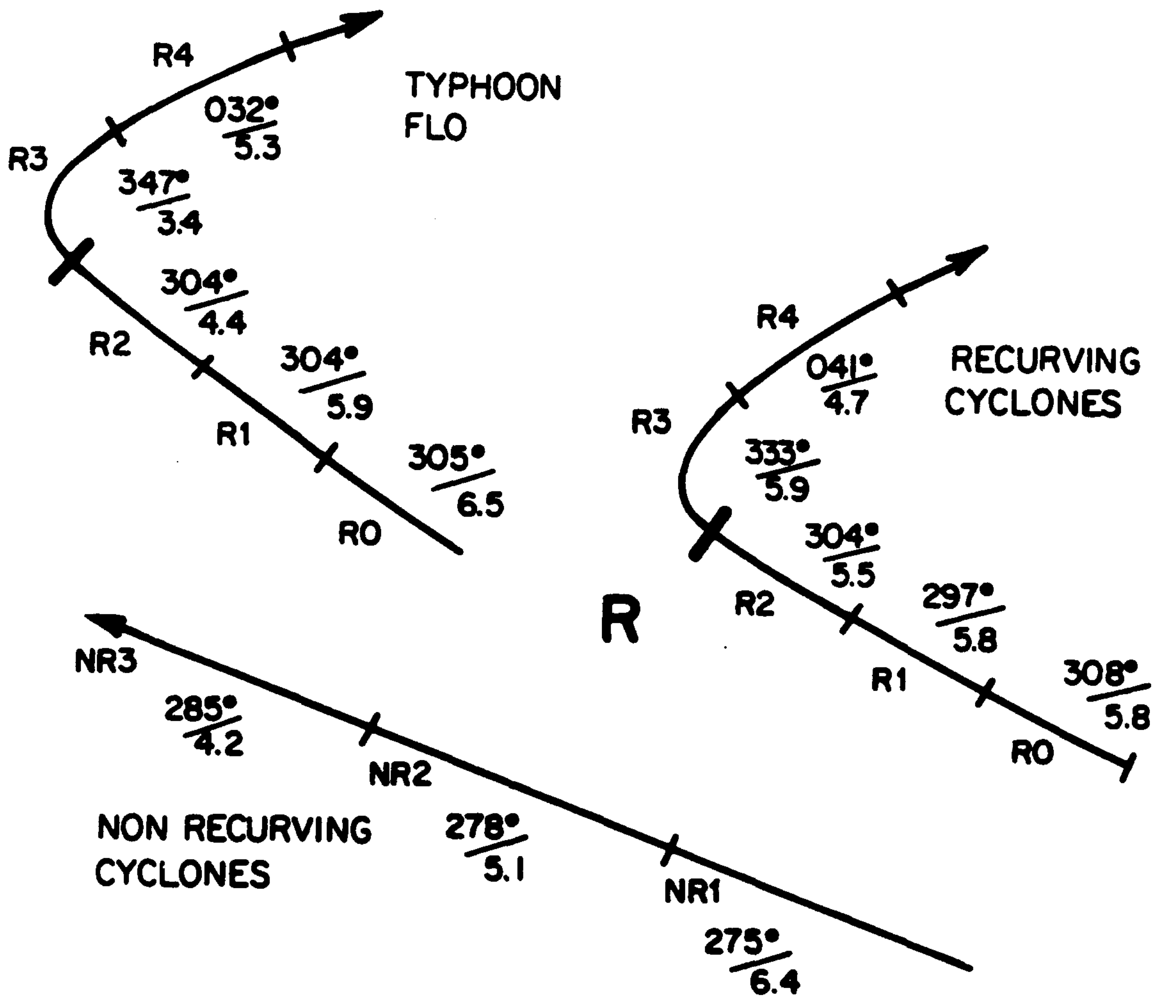


Figure 2.8: TCM-90 composite average speed and direction for the recurving, non-recurving, and for Typhoon Flo time periods. Units in m/s.

Table 2.1: Summary of TCM-90 non-recurving, recurving and Typhoon Flo time periods.

Name	Time Period	Description	Average Direction	Composite Speed (m/s)
Non	NR1	First 1/3 of track	275	6.4
Recurving	NR2	Second 1/3 of track	278	5.1
Cyclones	NR3	Last 1/3 of track	285	4.2
	R0	48-72 h before recurvature	308	5.8
Recurving	R1	24-48 h before recurvature	297	5.8
Cyclones	R2	0-24 h before recurvature	304	5.5
	R3	0-24 h after recurvature	333	5.9
	R4	48-72 h after recurvature	041	9.7
	R0	48-72 h before recurvature	305	6.5
Typhoon	R1	24-48 h before recurvature	304	5.9
Flo	R2	0-24 h before recurvature	304	4.4
	R3	0-24 h after recurvature	347	3.4
	R4	48-72 h after recurvature	032	5.3

2.5 TCM-90 Data Set

2.5.1 Rawinsondes

The TCM-90 rawinsonde data set covering the time span August through September, 1990, was composited and analyzed in the same manner as the 21-year Gray research project data set. Due to the intensive data gathering effort expended during this project, an unprecedented number of observations, in both geographical and temporal coverage, were available. This provided the opportunity to investigate individual cases of cyclone steering motion. The data sample size and coverage appeared sufficient to explore if meaningful quantitative steering flow for an individual storm could be obtained. Table 2.2 summarizes the numbers of rawinsonde observations which were used. Comparing data amounts we find that the TCM-90 experiment had approximately 15 percent of the rawinsonde data available during the August-September period of the 21-year data sample and about 7 percent of the data available during the entire 21-year period.

Table 2.2: Number of rawinsonde observations in composites by radial band and stratifications for (A) WNP 1957-77, (B) WNP (Aug-Sept) 1957-77, (C) TCM-90, (D) TCM-90 non-recurving, (E) TCM-90 recurving, (F) Typhoon Flo, (G) Typhoon Flo satellite winds.

A
Western North Pacific 1957-77

Radius	West Mover	North Mover	Northeast Mover
10	5776	5036	2652
8	4667	4436	2355
6	3627	3465	1940
4	2354	2349	1314
2	1012	1104	645

B
Western North Pacific (Aug-Sept) 1957-77

Radius	West Mover	North Mover	Northeast Mover
10	2524	2296	1023
8	2097	2012	902
6	1708	1631	789
4	1135	1141	576
2	491	584	295

C
TCM-90

Radius	West Mover	North Mover	Northeast Mover
10	474	264	219
8	406	229	167
6	293	185	150
4	169	163	104
2	96	72	57

Table 2.2: Continued.

D
TCM-90
Non-Recurring Cyclone Time Periods

Radius	NR3 Octant 3	2	1	NR2 3	2	1	NR1 3	2	1
10	22	35	43	36	67	47	16	48	22
8	33	32	40	27	63	41	13	40	15
6	20	19	36	23	51	50	6	28	24

E
TCM-90
Recurring Cyclone Time Periods

Radius	R4 Octant 3	2	1	R3 3	2	1	R2 3	2	1	R1 3	2	1	R0 3	2	1
10	20	18	17	28	21	21	29	14	15	12	10	10	3	5	3
8	16	12	16	18	19	17	15	7	8	13	6	4	2	5	3
6	9	11	16	14	8	10	16	6	3	5	6	5	1	4	0

F
Typhoon Flo
Recurring Cyclone Time Periods

Radius	R4 Octant 3	2	1	R3 3	2	1	R2 3	2	1	R1 3	2	1	R0 3	2	1
10	7	7	4	9	7	9	15	3	6	2	4	2	1	4	2
8	8	4	6	9	3	7	8	3	3	4	4	0	1	1	2
6	1	3	8	8	0	3	4	1	3	1	3	4	1	1	0

G
Typhoon Flo–200 mb Satellite Cloud-Drift Wind Observations
Recurring Cyclone Time Periods

Radius	R4 Octant 3	2	1	R3 3	2	1	R2 3	2	1	R1 3	2	1	R0 3	2	1
10	0	2	23	3	1	1	1	0	5	0	1	15	6	3	10
8	0	12	29	8	1	5	9	14	19	0	0	20	1	0	12
6	6	28	23	9	15	13	13	20	14	0	8	15	2	0	9

2.5.2 Satellite-Derived Cloud-Drift Winds

In addition to the rawinsonde data used from TCM-90, Japanese GMS satellite-derived cloud drift winds were available from three of the IOP's. Satellite wind data for the time period covering Typhoon Flo received special post-processing at the University of Wisconsin Satellite Data Center under the direction of Chris Velden. This wind vector information is considered to be of very high quality due to the careful editing and processing that the Wisconsin group provided. Satellite wind information was available at several levels in the atmosphere, with the majority of the data concentrated in the upper and lower troposphere (approximately 200 mb and 850 mb levels). A special computer program was developed by the Gray research project to composite this 200 mb satellite wind information in cylindrical coordinates and to compare it with the rawinsonde data in the same coordinates.

Chapter 3

TROPICAL CYCLONE STEERING MOTION

3.1 Steering Flow

Tropical cyclones typically move with directions and speeds very closely related to the broad-scale environmental flow fields in which they are embedded. This is referred to as the "steering current". There are, however, many questions as to how this steering current should be defined and if there are not systematic differences of TC motion to the basic steering flow.

There has been uncertainty as to the atmospheric level or layer that primarily determines tropical cyclone motion (Dong and Neumann, 1986). Some studies have demonstrated a higher correlation of tropical cyclone displacements with the flow at mid-tropospheric levels (e.g., Neumann, 1979; Pike, 1985). Neumann indicates that he attains somewhat better forecast performance through a mass-weighted deep-layer mean flow rather than a middle level steering current. Holland (1983) has stated that the asymmetric inflow-outflow jets present in the low level frictional layer and upper level outflow layers of the cyclone can significantly distort the basic current evaluations. The ONR experiment (Elsberry, 1985) has suggested that these layers were neglected and a mass-weighted 850-300 mb average has been used to define the basic current.

Through much additional observational analysis with different levels and radii it has been determined that, indeed, the best steering current for tropical cyclones appears to be the deep-layer (850-300 mb) and 5–7° radius mean wind flow (Gray *et al.*, 1988). However, significant deviations from the environmental flow are observed in composite studies by George and Gray (1976), Chan and Gray (1982), and Holland (1984) and in composites of operational analyses by Brand *et al.* (1981). In the mean over many storms, cyclones

of the Northern Hemisphere have been observed to deviate to the left from their basic current defined by azimuthal averages of the flow within radial bands around the cyclone (Chan and Gray, 1982; Elsberry, 1985).

3.2 Analysis Objectives

This study analyzes the differences in actual tropical cyclone motion to the steering current at various radii. The new TCM-90 data composites, and those generated by the Gray research project for all WNP cyclones in the 1957-77 data set are used. Indicators of the key radii for steering flow are obtained from the observational data bases. The goals are to:

1. Verify previous findings from a large 21-year composite data set for the period of August through September and a larger 21-year data sample of all months.
2. Compare these results with the much smaller though intensive two month (August through September 1990) observational period of the TCM-90 project.
3. Examine the composites of recurving and non-recurving storms observed during the TCM-90 project for possible forecast indicators to turning motion or recurvature.

3.3 Comparison of 1957-77 Composite Data Set Steering Motion to the TCM-90 Composites

Figures 3.1, 3.2, and 3.3 show the layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the mean cyclone motion. The TCM-90 composites (Aug-Sept, 1990) are compared to both the complete 21-year (1957-77) NWP composites compiled by the Gray research project, and to a smaller subset using just the Aug-Sept 1957-77 data. This was done to eliminate any seasonal bias that may occur and to allow for a more refined comparison. Table 3.1 gives the directional stratifications used for the west, north, and northeast composites.

Only tropical cyclones that had reached tropical storm intensity (17 m/s or greater) and were moving at least 2 m/s were included in the composites. This is done to eliminate very weak and disorganized cyclones and those that lack a definable direction of motion.

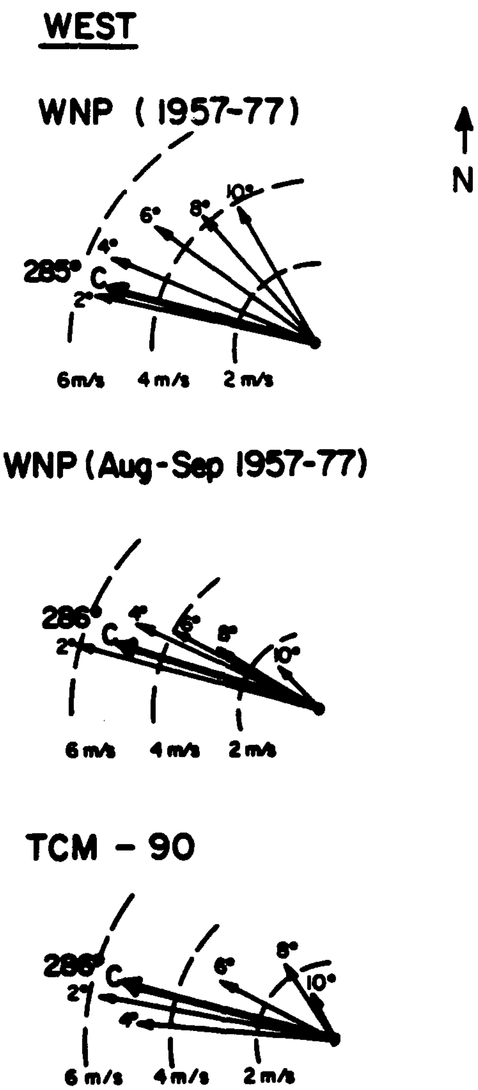


Figure 3.1: The layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the cyclone motion (denoted by a "C"). These diagrams are for all west moving cyclones from the three different data sets.

Table 3.1: Description of the cyclones stratified by direction.

STRATIFICATION	DESCRIPTION
West Moving Cyclones	240° < cyclone direction < 315°
North Moving Cyclones	315° < cyclone direction < 045°
Northeast Moving Cyclones	020° < cyclone direction < 090°

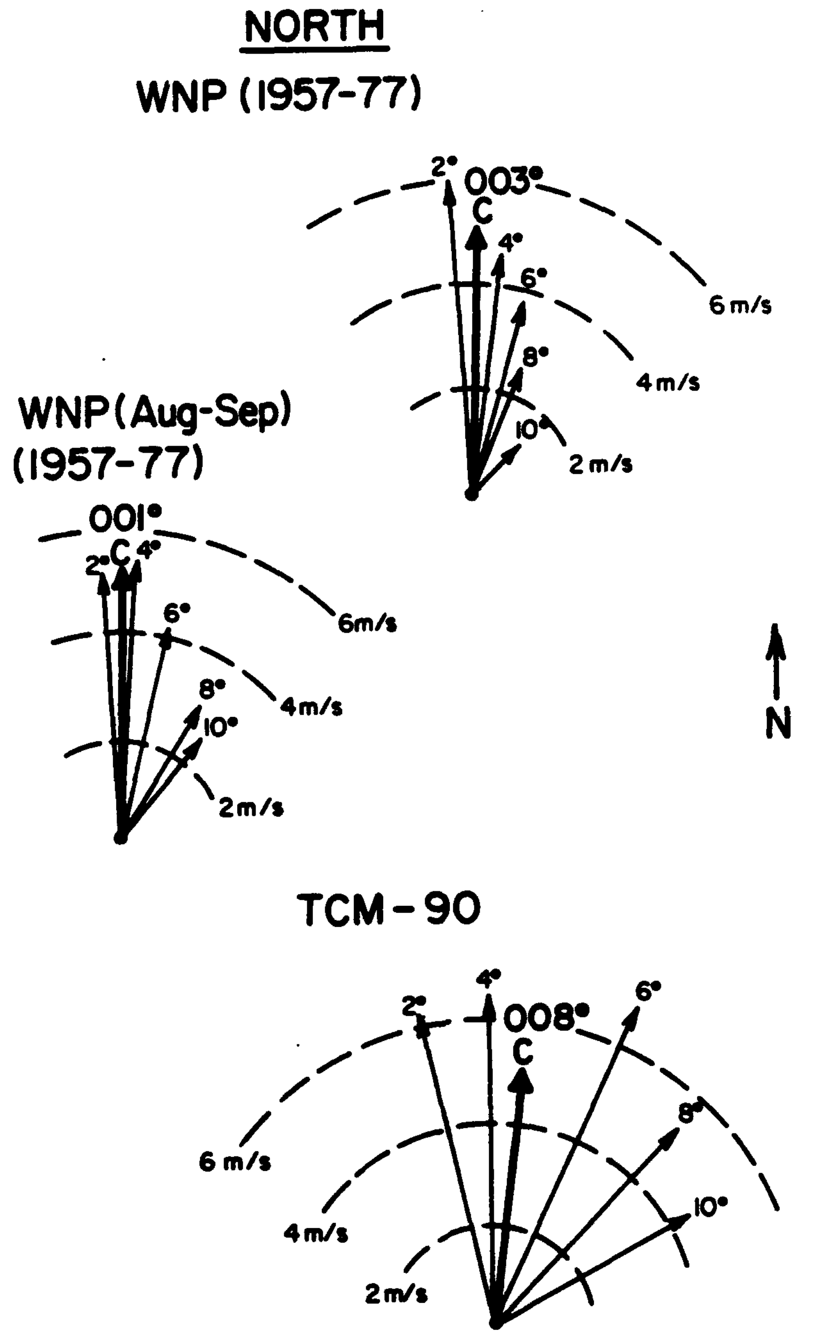


Figure 3.2: The layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the cyclone motion (denoted by a "C"). These diagrams are for all north moving cyclones from the three different data sets.

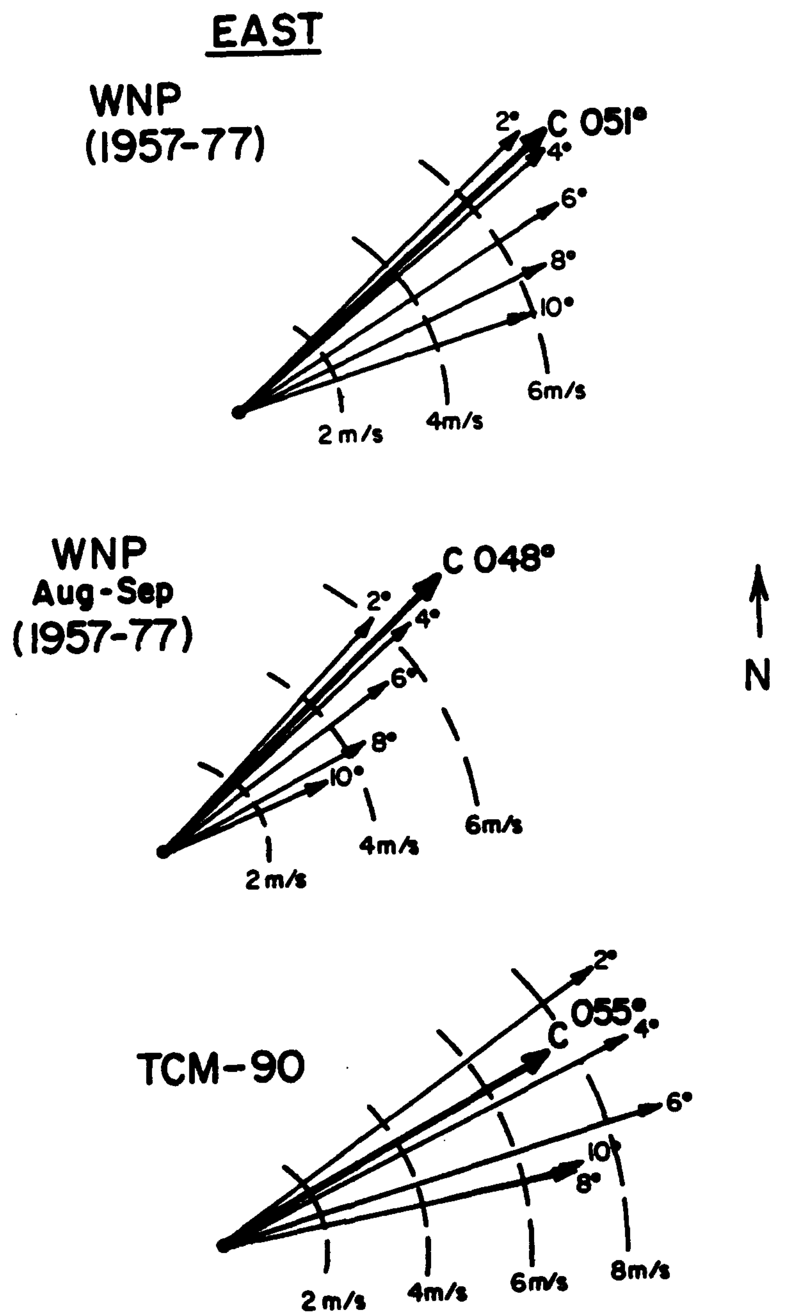


Figure 3.3: The layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the cyclone motion (denoted by a "C"). These diagrams are for all northeast moving cyclones from the three different data sets.

Summary

The results from the large data sets indicate that tropical cyclones move on average with a direction very close to their interior 3° radius tropospheric mean wind currents. The TCM-90 data set for a two month period in a single season showed a tropical cyclone motion direction closer to the 5° radius layer average wind for the west and north movers. The northeasterly movers from all data sets were in agreement that the 2° (850-300 mb) layer average flow best indicated the actual cyclone direction of motion. The speed of motion from the large composite data set was very close to the 2° radius mean composite wind speed. The TCM-90 set had the same composite wind speed magnitude as the larger data set, but indicated a 1-2 m/s slower motion than its' surrounding flow for both the north and northeast composites.

Discussion

The differences encountered between the TCM-90 data set composites and the much larger 21 year data set composites are most likely due to the data sample sizes involved. The TCM-90 composites contained at most several hundred observations versus the thousands of observations compiled in the larger data set (see Table 2.2). The unique global, synoptic, and mesoscale conditions present during the 13 TCM-90 storms may have included somewhat anomalous wind fields which may have resulted in slightly different relative steering motion than the much larger 21-year composites. There were certainly a wide variety of storm tracks included in the TCM-90 data set (see the Appendices for TCM-90 tracks). It is not unreasonable that in this smaller sample size that composite averages may be somewhat different from the much larger data samples.

3.4 Comparison of Steering Motion for TCM-90 Non-Recurving and Recurving Storms

Four TCM-90 storms were classified as non-recurving cyclones and three as recurving cyclones. These were composited into non-recurving cyclone time periods NR1 through NR3 and recurving cyclone time periods R0 through R4. Figure 3.4 shows the differences in steering flow found during recurving cyclone time period R2, just before recurvature,

and non-recurving cyclone time period NR2. Figure 3.5 compares period R3, during recurvature, with non-recurving period NR3. Figure 3.6 shows the individual non-recurving periods NR1, NR2, NR3, and the combined composite of the three periods.

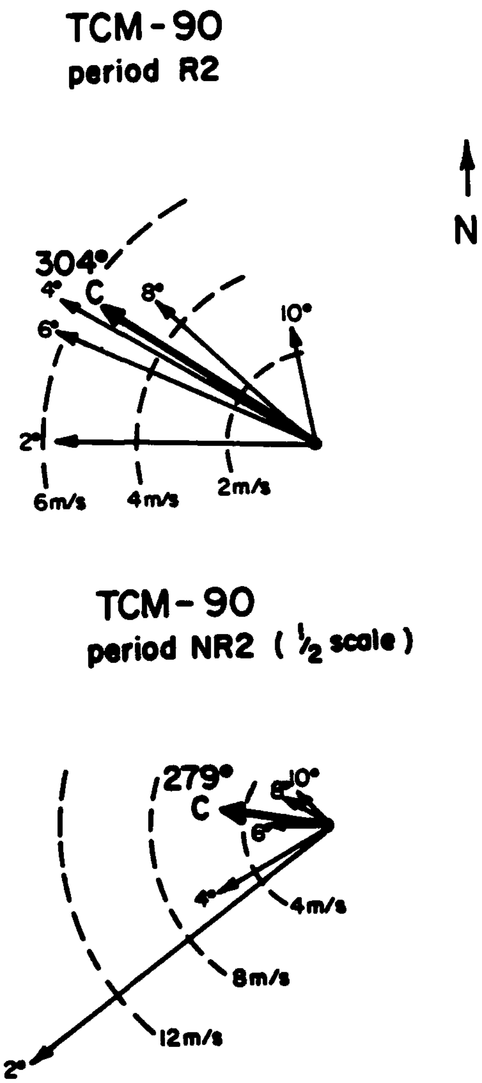


Figure 3.4: The layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the cyclone motion (denoted by a "C"). These diagrams show the composite results for TCM-90 recurving cyclones period R2 and non-recurving cyclones period NR2.

<u>Summary</u>

We observe in Fig. 3.4 that there is a much more pronounced SW flow evident at the 3-5° radius during non-recurving period NR2. It is more than twice the speed of the composite vector in period R2. Also, the outer 7-10° wind flow for R2 shows a greater

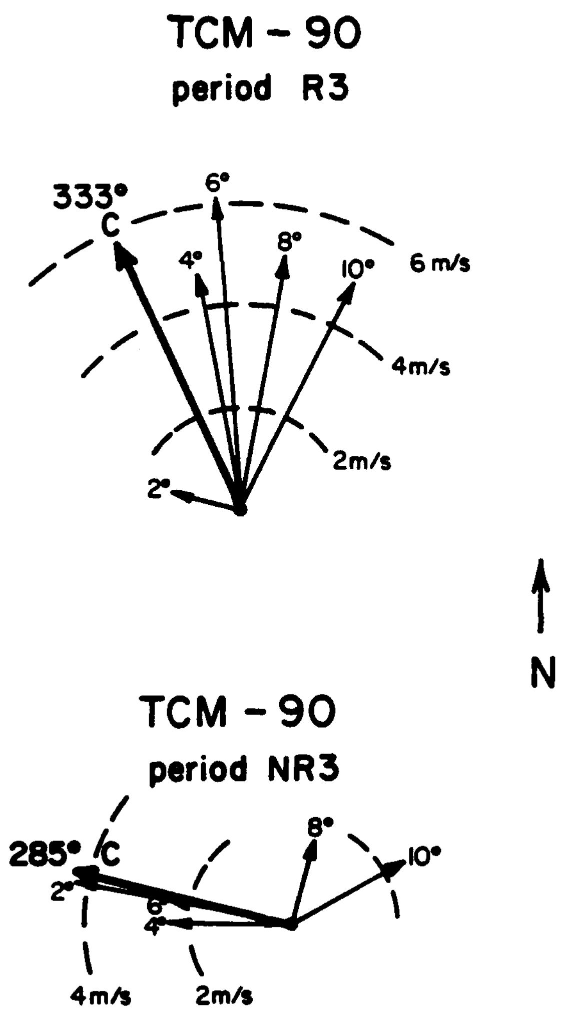


Figure 3.5: The layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the cyclone motion (denoted by a "C"). These diagrams show the composite results for TCM-90 recurving cyclones period R3 and non-recurving cyclones period NR3.

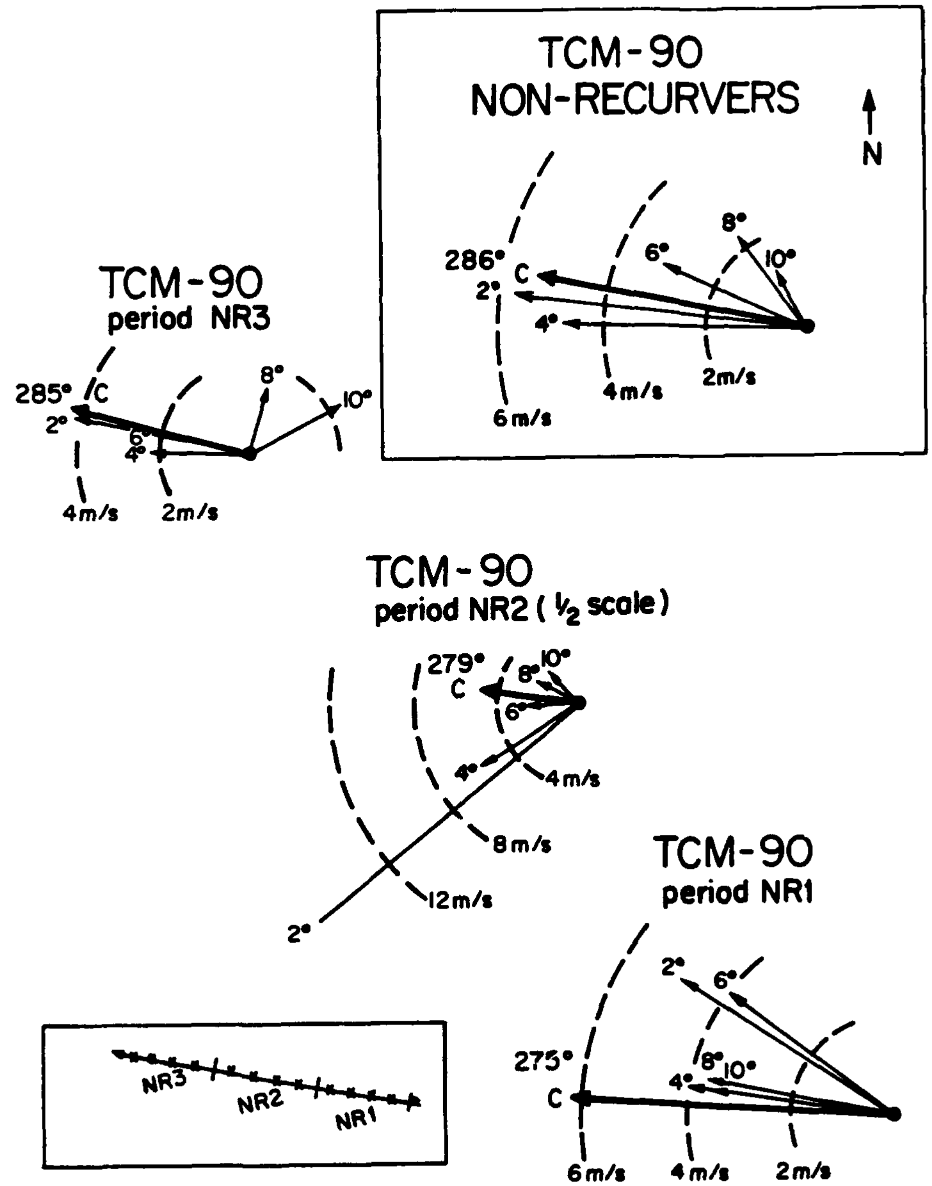


Figure 3.6: The layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the cyclone motion (denoted by a "C"). These diagrams show the composite results for TCM-90 non-recurving periods NR1 through NR3 and the combined composite including all three time periods.

magnitude in the northwesterly direction than that for NR2. However, the inner 3-5° flow on R2 is not dramatically at variance from a westerly course.

In Fig. 3.5 there is an obvious change in the steering flow. The 3-5° flow maintains itself for NR3 in a predominantly westerly direction. R3 indicates mostly NW to N flow at this radius.

Figure 3.6 illustrates the variance encountered in individual time period composites. However, the overall composite of the three non-recurving time periods results in steering motion comparable to the 21-year data set steering motion for west moving cyclones.

Discussion

It should be noted that even though NR3 shows N to NE flow at the 8-10° outer radius, the 3-5° flow best fits the actual cyclone motion. This indicates that recurvature will not take place. This point is examined further in Chapter 5.

It is interesting to note the large variance in the different time period vectors. The individual time period motion vectors indicate a mean flow which can be significantly different from average data sets.

In terms of recurvature forecasting, there does not appear to be clear 850-300 mb steering flow differentiation between non-recurving and recurving cyclones at the critical phases of the storm track motion such as during period R2 or NR2. This lack of a clear difference in steering flow signal would preclude the timely forecasting of recurvature on an operational basis from typical steering flow information alone. The period immediately before recurvature (R2) in TCM-90 is subject to a very large set of wind varying influences that could cause the composite data set to give ambiguous information in a recurving composite sample size of only three cases. For a single storm case, even with enhanced data coverage, it is unlikely that a forecaster would have much confidence in predicting the start of a right turning motion from the steering flow indications alone.

3.5 Comparison of Typhoon Flo (Periods R0 through R4) Composite Steering Flow to TCM-90 Non-Recurving Storms Composite Steering Flow

Figure 3.7 compares a combined composite for Typhoon Flo, a recurving TCM-90 cyclone during periods of R0 through R4 to three composite TCM-90 non-recurving time

periods. Both TCM-90 composites show a similar key radius of steering motion at approximately 5°. The 2° radius vector for Typhoon Flo shows a highly anomalous eastward direction.

Discussion

For a larger overall TCM-90 composite data set such as all non-recurvers, or even the complete Typhoon Flo track composite, we see a more consistent result in comparison to the individual time period composites. The individual composite periods appear not to contain enough observations as to be representative enough as to give a reliable steering flow current.

3.6 Steering Flow Summary

Comparison of two independent data sets reveal similar results on the key steering flow radii which determine cyclone motion. The Gray project 21 year data set and the TCM-90 data set show the steering radii to be 5-7°. Given the size differential and temporal coverage between the two data sets, the TCM-90 results verify and compare favorably with the past results. Finally, there is some evidence available in the layer average wind flow information to differentiate between recurving and non-recurving cyclones. However, this difference may not show up in a timely fashion and give clear indications that would aid in specific recurvature or non-recurvature forecasts of initial turning motion.

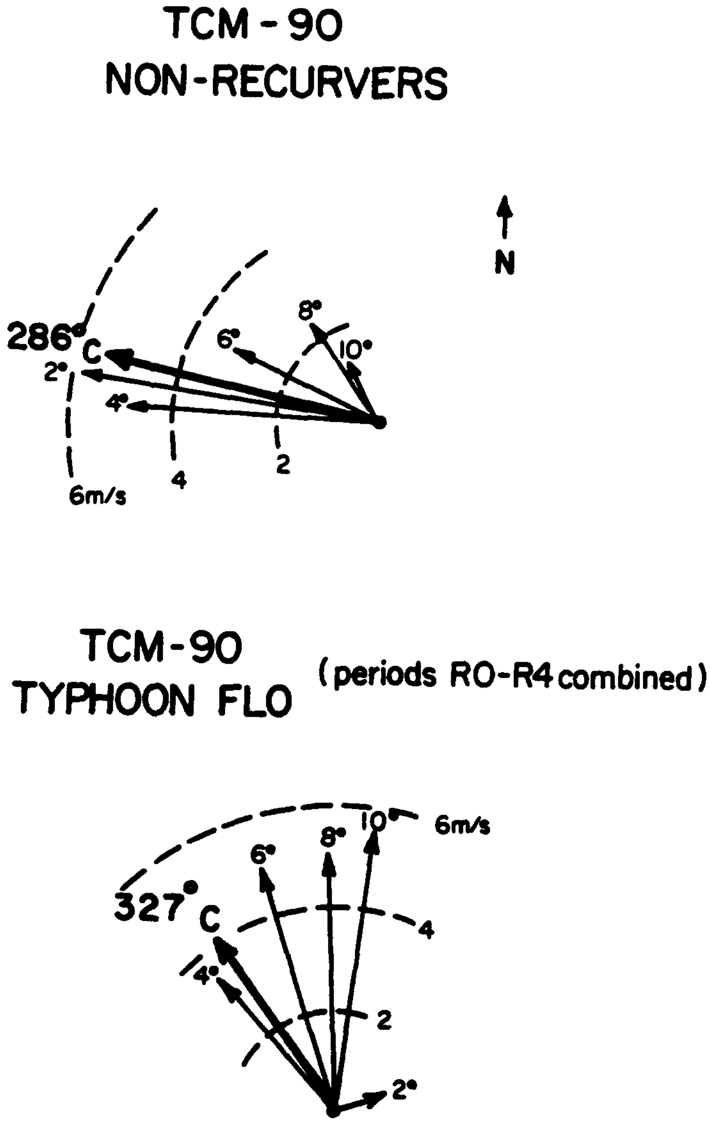


Figure 3.7: The layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the cyclone motion (denoted by a "C"). These diagrams show the composite results for all non-recurving periods combined, and a combined composite of recurving periods R0 through R4 for Typhoon Flo.

Chapter 4

STATISTICAL ANALYSIS OF WIND VARIABILITY

4.1 Data Variability

Working with large quantities of real-world observational data naturally brings up the question of surrounding individual case and time period cyclone steering flow variability and its reliability for cyclone motion. How large are individual case and time period variations in the measured surrounding cyclone wind field? What are reasonable ranges to be expected given the measurement systems, navigation, and data processing procedures.

4.2 Sources of Measurement Variations

There are obviously a myriad of small and large unrepresentative measurement and instrument inconsistencies that can occur in the collection of rawinsonde data, especially in data collected near the tropical cyclone center. Some of the major data inadequacies are: (1) Different cyclone structure and surrounding flow influences. Every storm is unique and different in its characteristic, intensity, size, and areal coverage of outer winds. This can have a significant impact upon the wind fields surrounding a storm. (2) Natural variability within the storm due to convective features, etc. Winds are gusty and unrepresentative when taken near convective-scale features. (3) Measurement conditions. Every instrument has characteristic limitations and error sources. The sensing, transmitting, receiving and processing of atmospheric data can introduce unrepresentative steering flow features. (4) Compositing limitations. Even if the data were 100 percent accurate, there are some positioning and temporal unrepresentativeness which are introduced into each composite analysis. A large data set is required to eliminate these inherent positioning inconsistencies.

Given these data inaccuracies, what ranges of observational spread are to be expected for various classes of tropical cyclone motion?

4.3 Data Spread

In order to understand the degree of reliability and significance of the composite data, basic statistical analyses have been performed on the TCM-90 rawinsonde and satellite wind data composites. These tests were performed to learn of the typical scatter of individual parameter values about their means.

Figure 4.1 shows the typical 200 mb zonal wind component spread by octant for the TCM-90 composite period NR1 of non-recurvature at 200 mb and 6° radius. The average standard deviation about the mean value is about ± 6 m/s. The individual sounding deviations for an octant mean vary from 0.9 m/s to 9.7 m/s.

Figure 4.2 illustrates a similar standard deviation of wind at 200 mb and 6° (or 5-7° radius) of around 6-7 m/s for the second or NR2 period of recurvature. With the exception of octant 4, this wind spread is more uniform. The larger sample size available for the NR2 composites results in smoothing out of the spread to a consistent 7 m/s for all octants. Figure 4.3 examines the spread in the R2 period composite of Typhoon Flo just before recurvature. Several octants had no observations in them. The octants that did have observations showed a slightly lower average standard deviation of 4-5 m/s.

A comparison of zonal winds at 200 mb at 8° radius for Typhoon Flo for the period of R2 versus NR2 in selected octants is shown in Fig. 4.4. It clearly depicts the dramatic zonal wind differences observed between Typhoon Flo period R2 and NR2 in octants 1 and 2. The probability that Flo R2 zonal wind values at 8° radius in octant 1 are no different than the NR2 observed zonal winds is 3×10^{-7}.

Performing a similar statistical t-test on zonal winds in octant 3, there is little statistical probability that the two data sets are different. A 98% confidence level t-test on Flo period R2 in octant 3 gives a confidence interval of (-10.7,4.4) m/s. For period NR2 in octant 3 we get (-9.7, -2.1) m/s. The probability that an observed Flo period R2 zonal wind value in octant 3, 4, or 6 falls in the NR2 data range is, by contrast, with the octant 1 and 2 information, quite high.

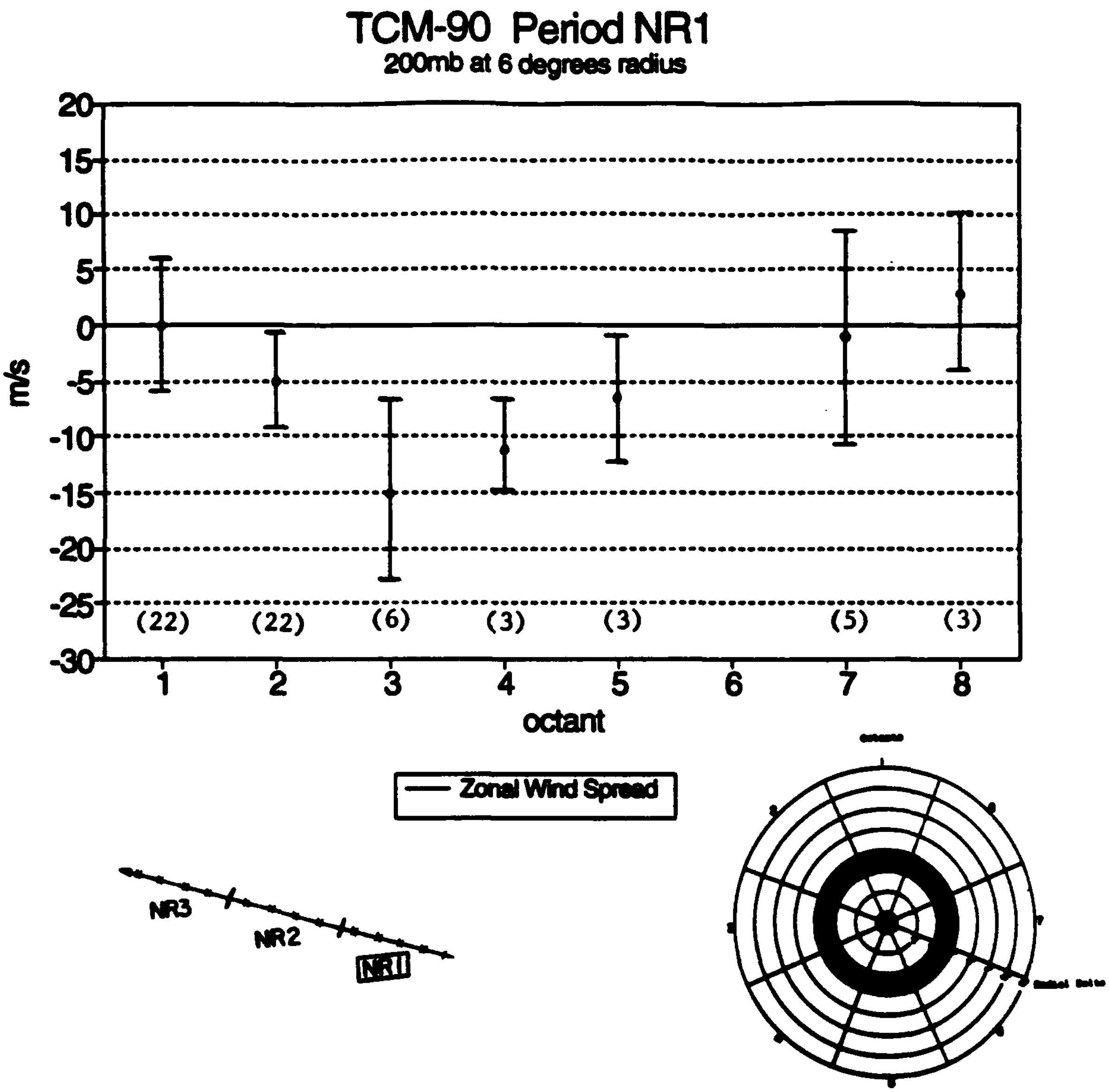


Figure 4.1: Standard deviation of zonal wind (in m/s) for TCM-90 period NR1 at 200 mb and 6° from the cyclone center. The vertical lines bracket the standard deviation of values. The numbers in parentheses indicate the number of observations.

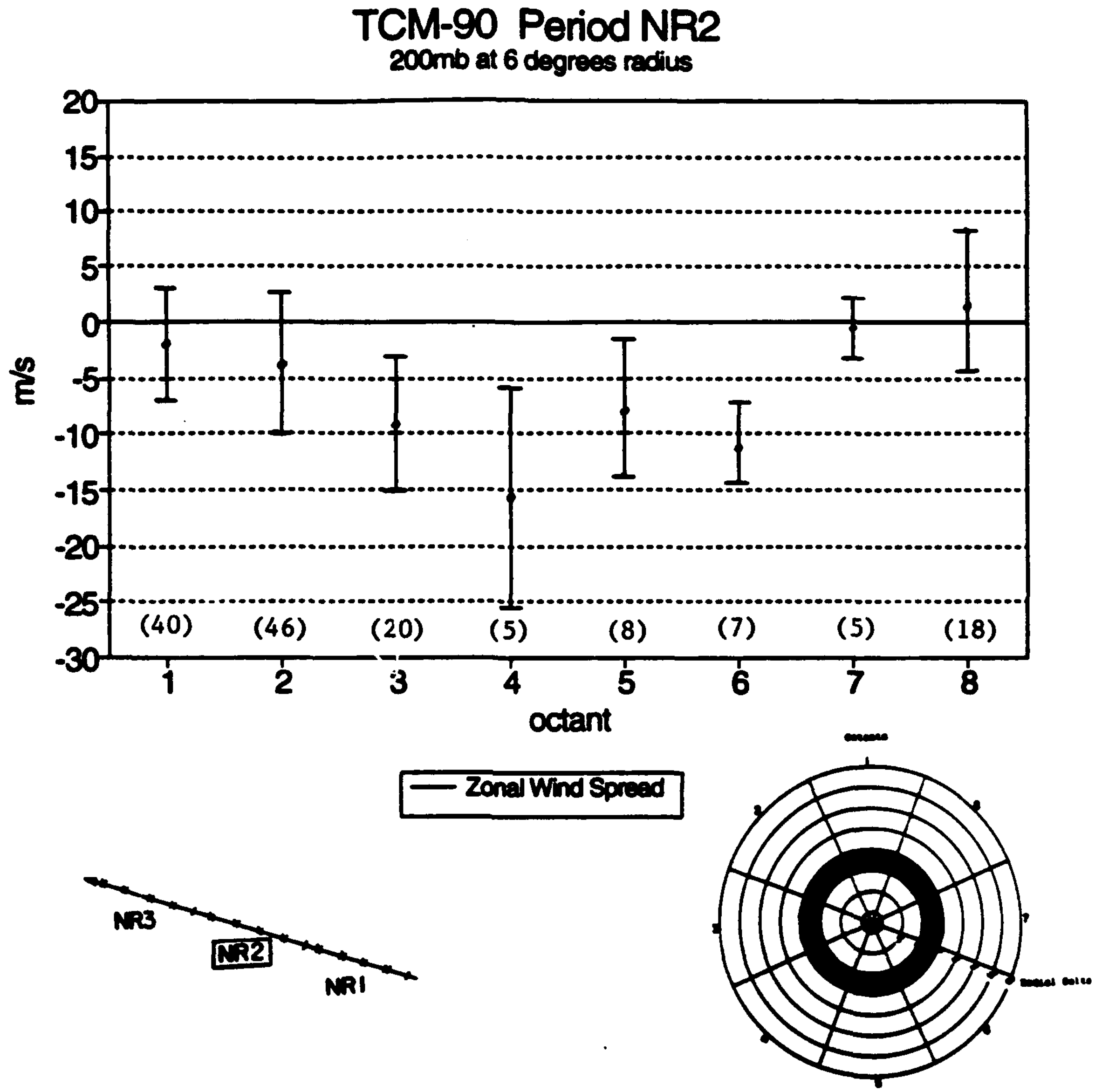


Figure 4.2: Standard deviation of zonal wind values (in m/s) for TCM-90 period NR2 at 200 mb and 6° from the cyclone center. The vertical lines bracket the standard deviation of values. The numbers in parentheses indicate the number of observations.

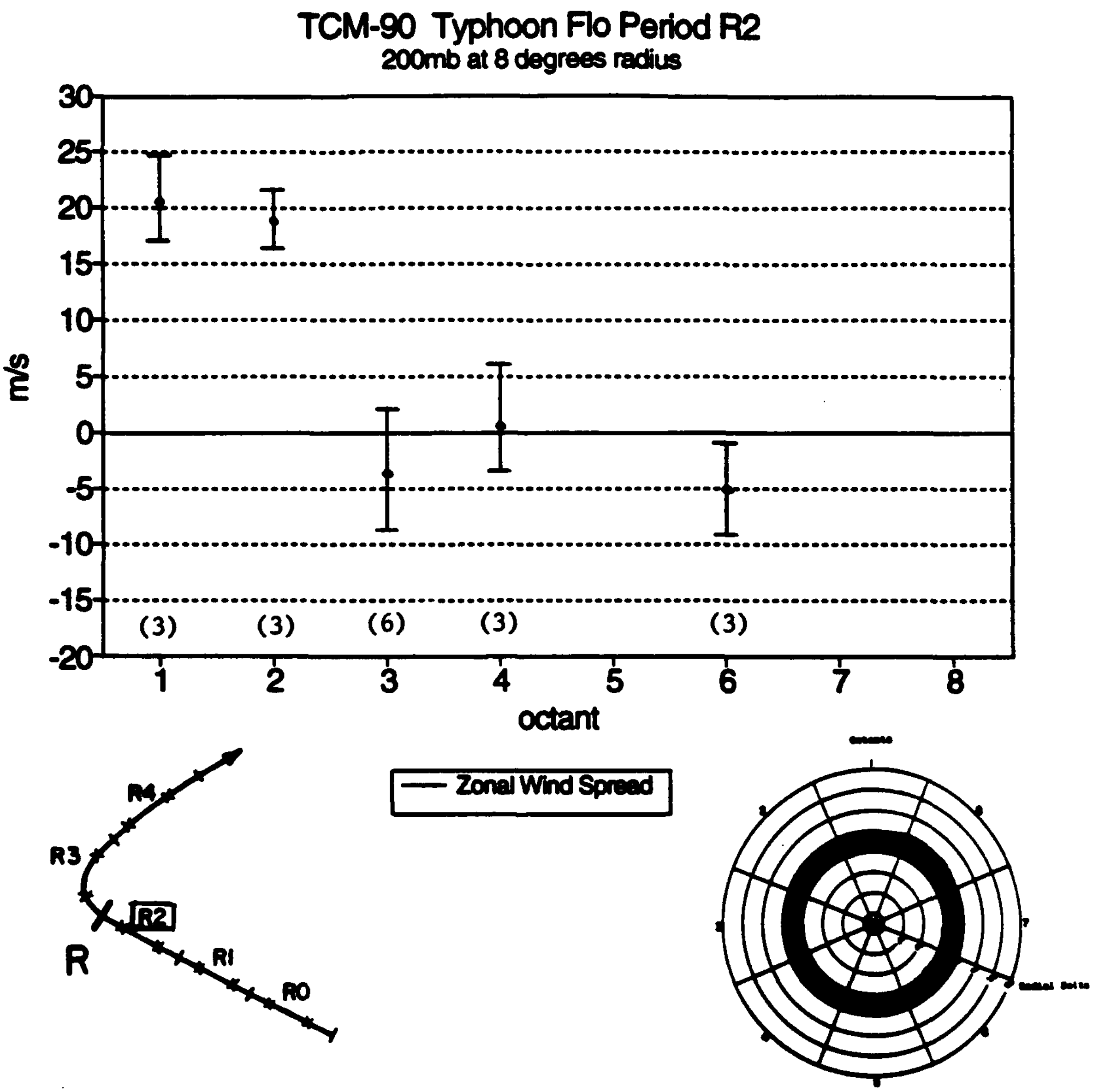


Figure 4.3: Standard deviation of zonal wind values (in m/s) for TCM-90 Typhoon Flo period R2 at 200 mb and 8° from the cyclone center. The vertical lines bracket the standard deviation of values. The numbers in parentheses indicate the number of observations.

The results of these tests indicate the importance of the zonal wind differences found to the north and northwest of recurving versus non-recurving cyclones. The observed zonal wind differences in octants 1 and 2 are clearly much larger than the typical spread of zonal winds. These differences can be used as a predictor. In other octants, such as 3, 4 and 6, recurvature versus non-recurvature differences are too small to be beyond the normal expected range of wind variability.

4.4 Standard Deviation of Satellite Cloud-Drift Winds

Table 4.1 shows the standard deviations of 200 mb satellite cloud-drift winds at 6, 8, and 10° radius from the cyclone center in octant 1 for the five 24-hour time periods for Typhoon Flo. The typical S.D. of these satellite winds was about 6 m/s. The average S.D. of these satellite winds is thus found to compare very favorably with the S.D. of the rawinsonde data. The satellite winds in this data set were very carefully reprocessed after the field experiment was completed.

Table 4.1: Standard deviations (in m/s) of Typhoon Flo for 200 mb satellite derived cloud-drift zonal winds. Values are for octant 1 and for periods R0 through R4 at three radial belts from the storm center.

Typhoon Flo Satellite Wind Standard Deviations
Octant 1
Period

Radius	R4	R3	R2	R1	R0
10	8.6	3.9	6.8	4.6	16.2
8	6.5	2.9	5.8	5.3	8.8
6	5.3	N/A	4.7	3.5	5.5

4.5 Summary

Standard deviation of individual octant and 2° radial belt values from past Gray research project composite winds indicated that there was about 8 m/s spread in zonal and meridional wind components at the upper tropospheric level (see Table 4.2). These larger composites involved thousands of soundings, versus the hundreds available for most of the TCM-90 time periods studied. From both of these studies we can determine an

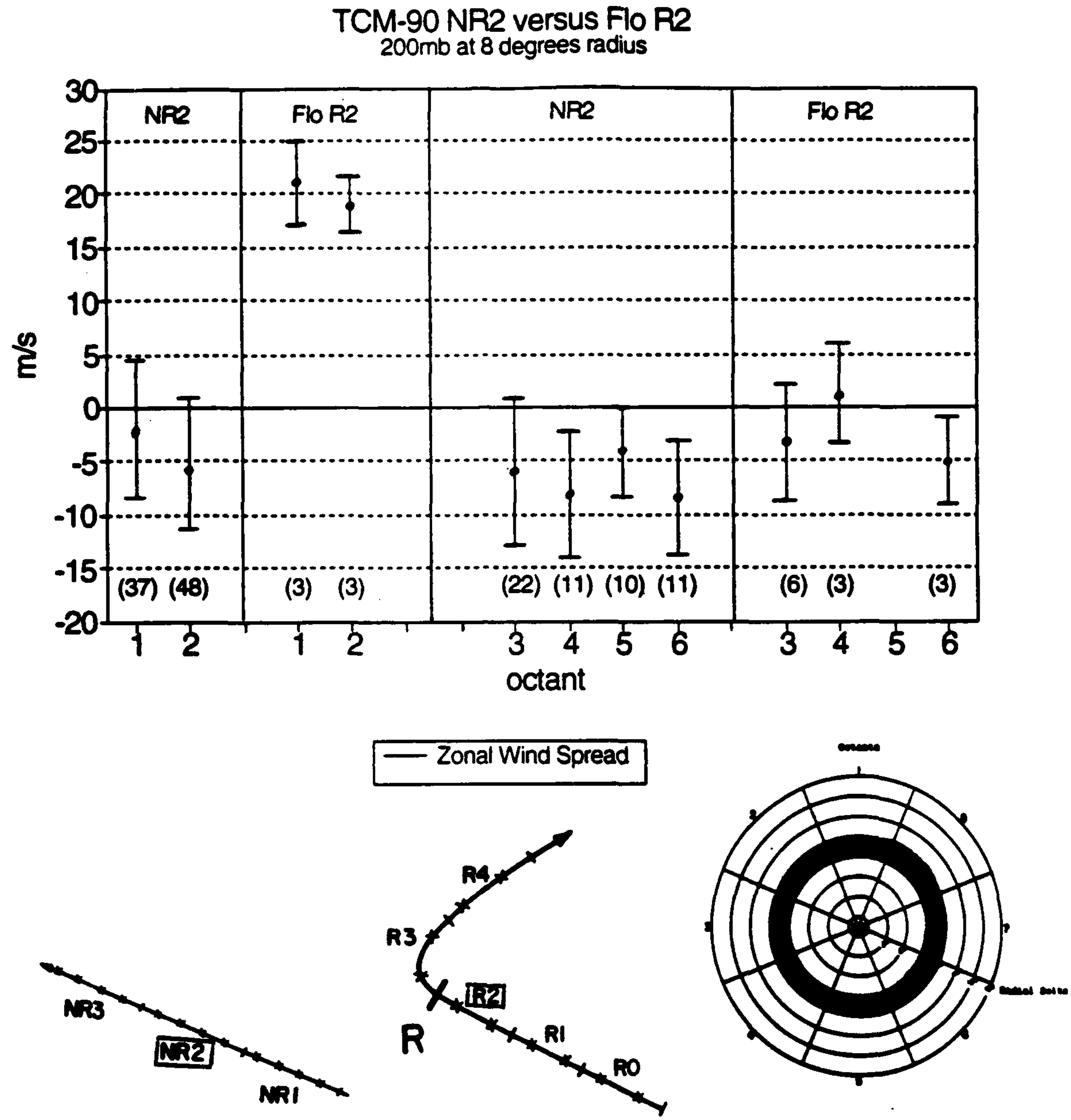


Figure 4.4: Standard deviation of 200 mb 8° zonal wind values (in m/s) for TCM-90 non-recurving cyclones period NR2 compared to Typhoon Flo period R2. The vertical lines bracket the standard deviation of values. The numbers in parentheses indicate the number of observations.

expected range of composite zonal wind values of about 7-8 m/s. The spread at lower levels is somewhat smaller.

Table 4.2: Approximate standard deviations of various wind components from individual octant wind averages at specific levels in m/s for data sets between 1957-1977 (from Gray, 1981).

	900 mb	500 mb	200 mb
Zonal wind (u)	~ 5	~ 5	~ 8
Meridional wind (v)	~ 5	~ 5	~ 8
Tangential wind (V_θ)	~ 5	~ 5	~ 8
Radial wind (V_R)	~ 5	~ 5	~ 8

Chapter 5

ENVIRONMENTAL WIND FIELDS—COMPARISON OF RECURVING AND NON-RECURVING CYCLONES

5.1 Introduction

Previous studies have attempted to identify features in the wind fields surrounding tropical cyclones which are conducive to recurvature (Hodanish, 1991; Chan and Gray, 1982, and others). It is accepted that the turning motion of tropical cyclones is controlled by their large scale flow surrounding them (Elsberry, 1988). We will now analyze those flow feature differences that distinguish tropical cyclone recurvature from non-recurvature.

Hodanish (1991) examined how the environmental wind fields of non-recurving cyclones differ from those recurving cyclones prior to the beginning of recurvature. Table 5.1 from Hodanish (1991) emphasizes the importance of examining the upper tropospheric (100-300 mb) zonal winds to the north and northwest (octants 1 and 2) of the cyclone's center to find differences between recurvature and non-recurvature. The maximum zonal wind differences are observed in octants 1 and 2, whereas there are negligible observed differences to the south and east (octants 4 through 7). His results were based on rawinsonde composites from a 21 year (1957-77) data set. This study will use composites from the TCM-90 data set to compare with his results and also attempt to determine if an individual case (Typhoon Flo) of recurvature could be shown to quantitatively resemble the larger data set.

5.2 Typhoon Flo

Figure 5.1 presents the best track of Typhoon Flo (JTWC, 1991). Typhoon Flo maintained a west-northwesterly movement of approximately 12 knots for almost eight

Table 5.1: Zonal wind differences between sharply recurving cyclones prior to recurvature (period R2) and the non-recurving cyclones (Hodanish, 1991). Units in ms^{-1}

Sharply Recurving Cyclones (Period R2) Minus Non-recurving Cyclones

Zonal Wind Differences–8 Degrees from Cyclone's Center

P (mb)	Oct 1	Oct 2	Oct 3	Oct 4	Oct 5	Oct 6	Oct 7	Oct 8
100	14.5	16.6	7.8	1.8	4.3	3.5	2.9	9.3
200	15.4	16.3	8.7	3.7	3.0	0.4	1.9	4.8
300	9.7	17.6	10.0	2.4	1.4	1.3	0.6	3.7
400	8.5	13.8	8.6	-0.4	-0.1	4.2	-0.7	3.7
500	6.6	11.6	5.9	-0.1	-1.2	-0.5	-0.2	3.7
600	3.8	6.8	2.4	-1.3	-2.5	-0.5	1.4	4.0
700	3.0	4.3	-0.7	-1.8	-2.1	1.7	0.7	2.8
800	3.1	2.2	-0.7	-2.1	-3.3	2.5	-0.5	2.7
Layer Ave.	8.1	11.2	5.3	0.3	-0.1	1.6	0.8	4.3

days until encountering a trough to its northwest which in time acted to recurve Flo's track to the northeast. Typhoon Flo had an unusually large number of rawinsonde and satellite wind observations surrounding it. It was chosen for analysis because of its data prevalence and because it provided an excellent near classical example of cyclone recurvature.

5.3 Zonal Wind Fields for TCM-90 Non-Recurving Cyclones

Figures 5.2 and 5.3 show the 6° and 8° zonal wind profiles respectively for the three TCM-90 non-recurving time periods in octant 1 on the north side of the cyclone. Figures 5.4 and 5.5 present similar profiles for octant 2 to the northwest.

Discussion

The 6° zonal wind profiles show that zonal winds in both octants for all three non-recurving time periods are from an easterly direction throughout the troposphere except in octant 1 where the zonal winds in the upper troposphere are from a weak westerly direction. The 8° profiles show that the zonal winds in octant 1 at periods NR1 and NR2 are negative, but at period NR3 it is found that positive zonal winds have penetrated into the mid and upper troposphere.

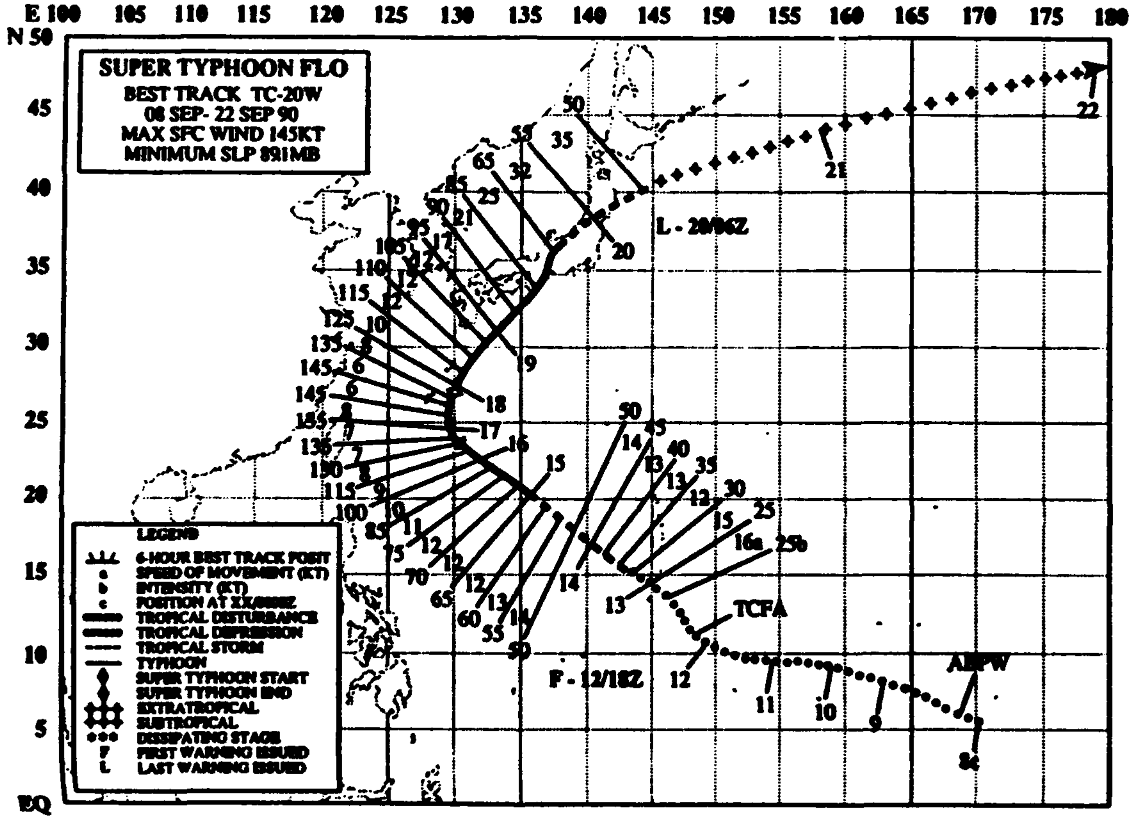


Figure 5.1: Best track for Typhoon Flo. (JTWC, 1991)

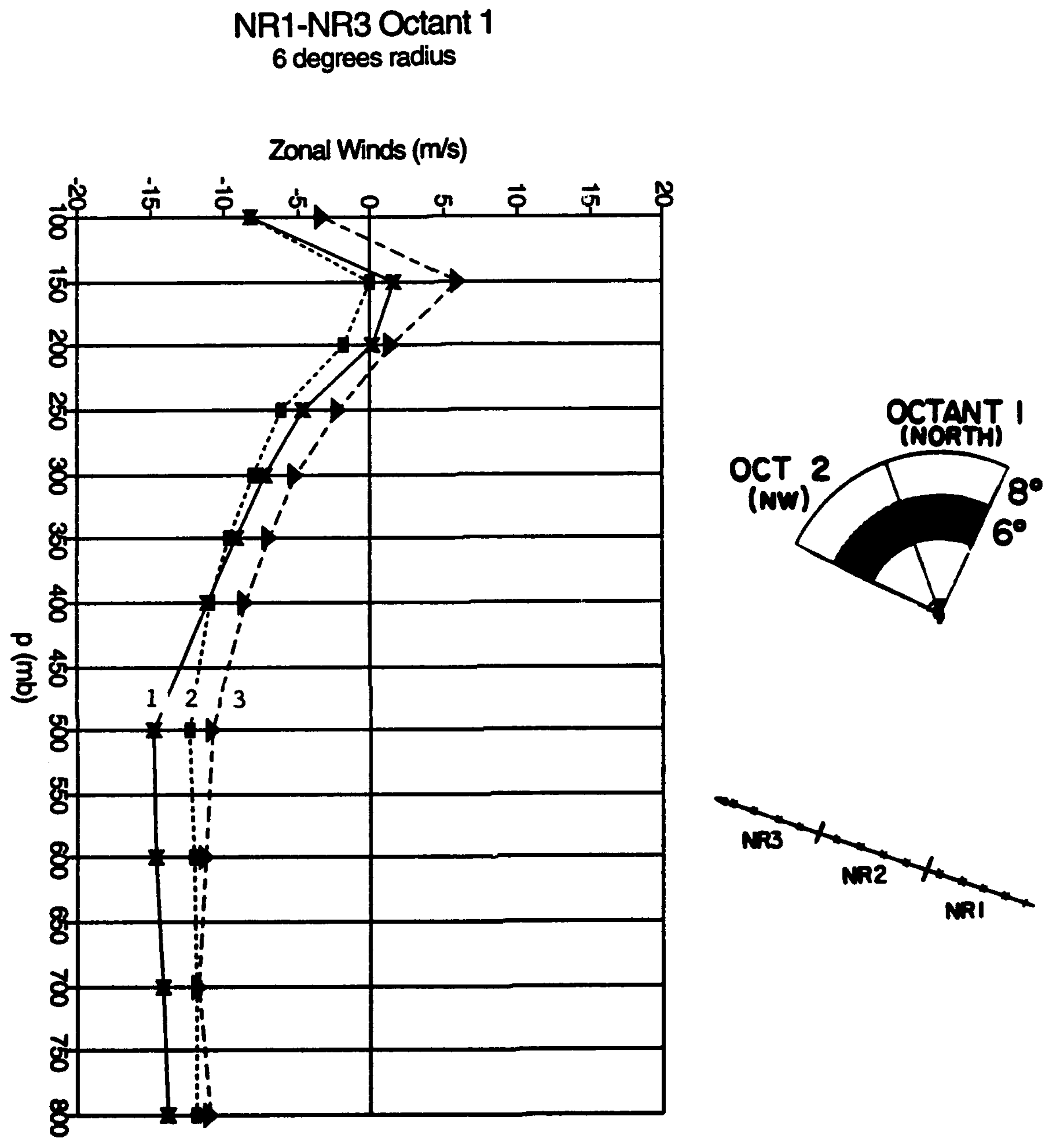


Figure 5.2: Zonal wind vertical profile for periods NR1 through NR3 in octant 1 at 6° radius from the cyclone center.

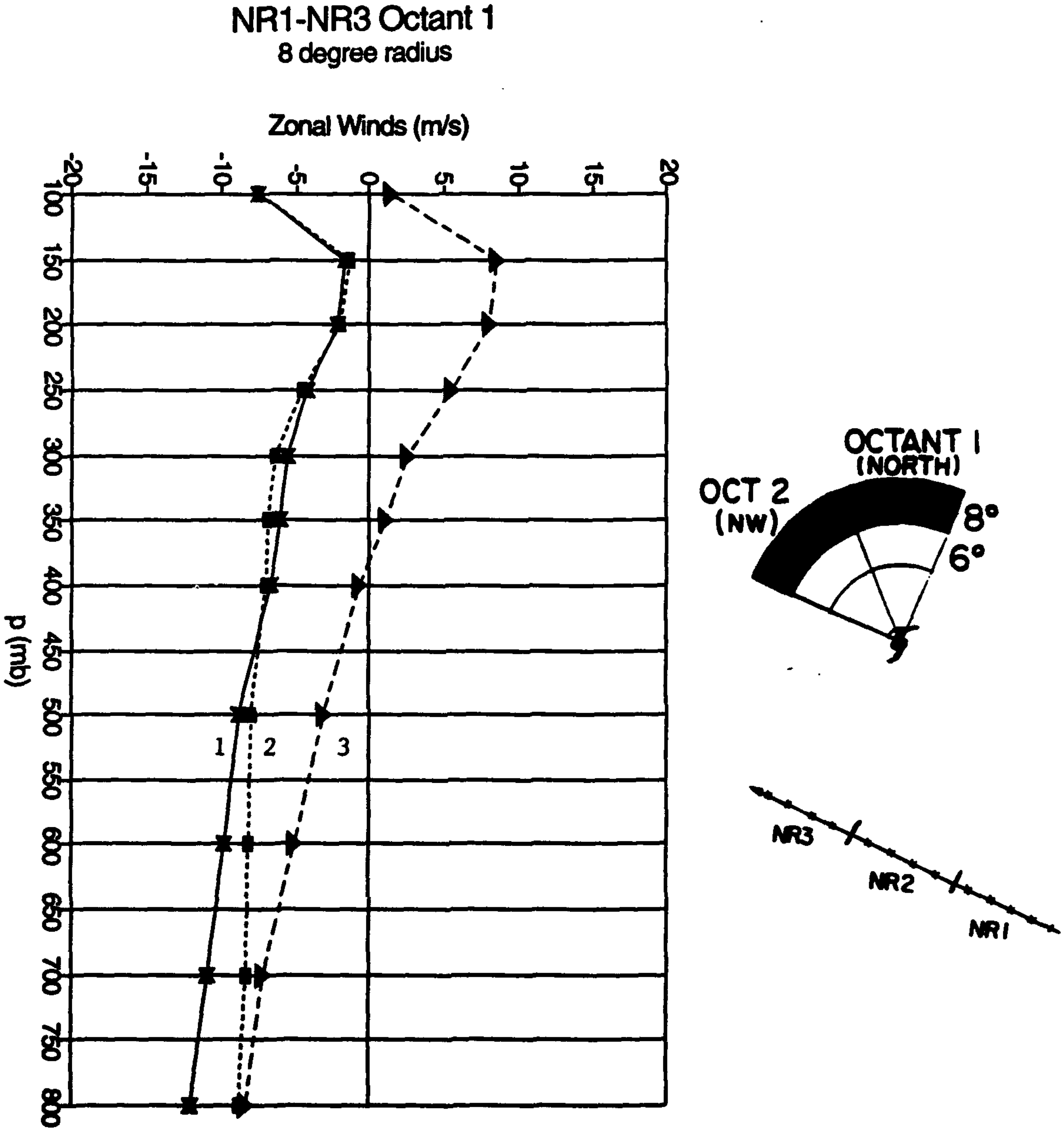


Figure 5.3: Zonal wind vertical profile for periods NR1 through NR3 in octant 1 at 8° radius from the cyclone center.

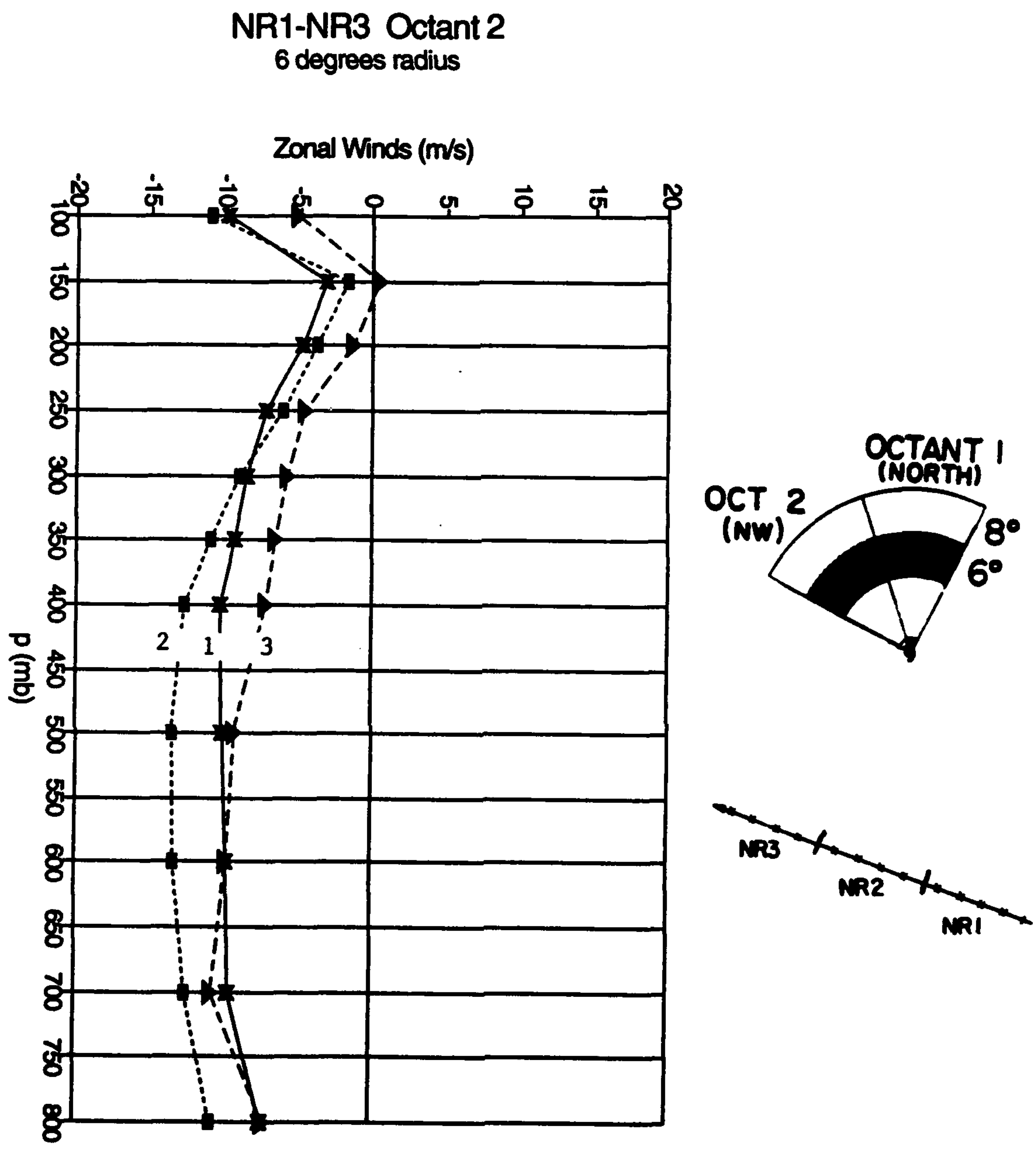


Figure 5.4: Zonal wind vertical profile for periods NR1 through NR3 in octant 2 at 6° radius from the cyclone center.

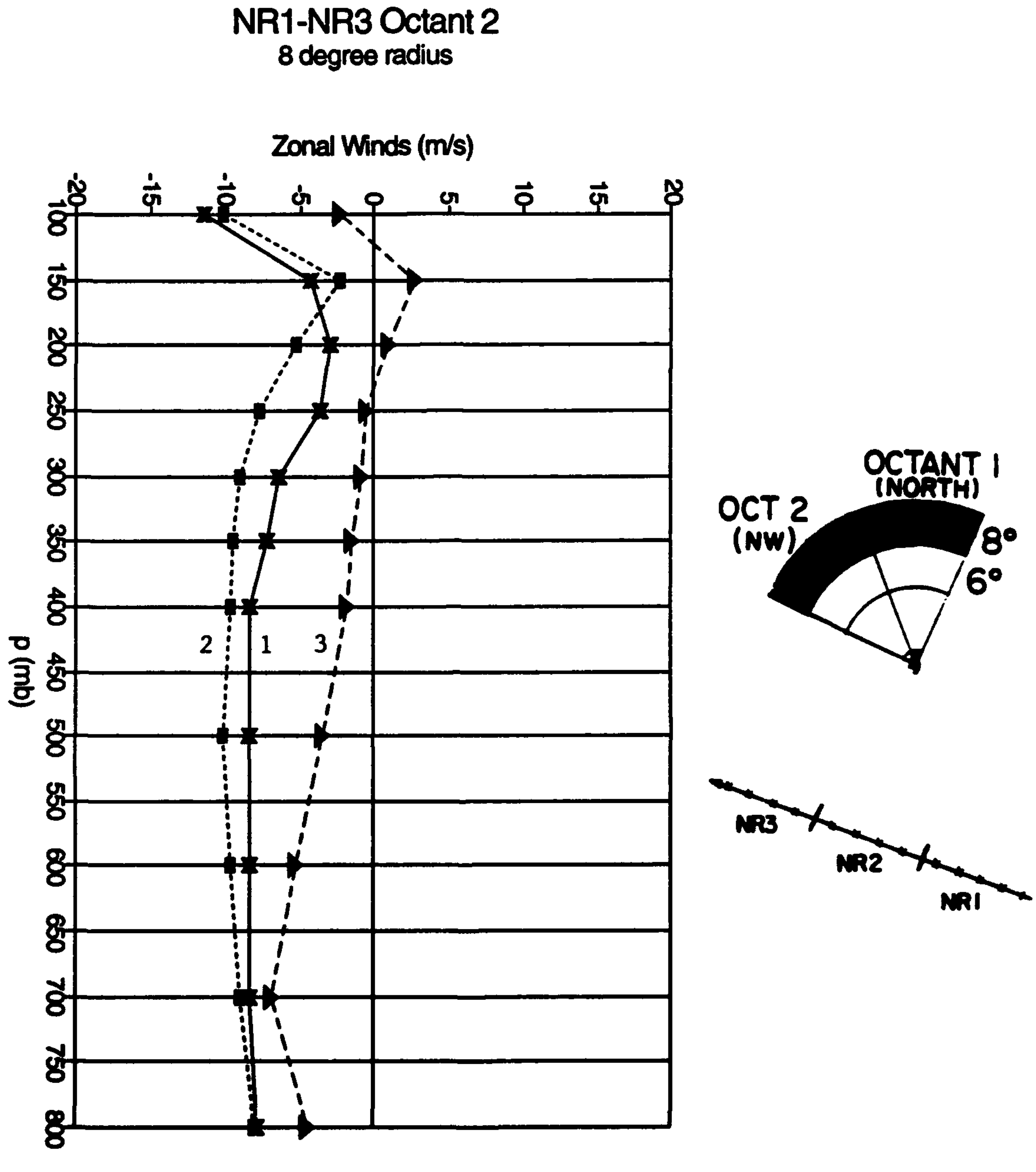


Figure 5.5: Zonal wind vertical profile for periods NR1 through NR3 in octant 2 at 8° radius from the cyclone center.

TCM-90 cyclones which moved west throughout their lifetimes were observed to be imbedded in a deep easterly flow at nearly all levels in the troposphere at 6° radius. The zonal wind fields at 8° were also from an easterly direction throughout most of the levels of the troposphere except during the last time period, NR3. During the latter period, positive zonal winds have penetrated into the mid and upper troposphere to the north and northwest of the cyclone. Hodanish (1991) states that these positive zonal winds are most likely associated with the mid latitude westerly wind regime that appear near eastern Asia during this last time period. Tropical cyclones which track in this direction will eventually move to higher latitudes and approach the southern limits of the mid-latitude westerly wind regime. The important feature of note is that for the TCM-90 cyclones, the westerlies penetrated the mid and upper troposphere 8° to the north and northwest of the westward moving cyclones and yet had no effect on altering their direction of motion.

5.4 Zonal Wind Fields for Typhoon Flo

5.4.1 Rawinsonde Composite Results

Figures 5.6 and 5.7 show the zonal wind profiles at 6° radius for the five recurving time periods R0 through R4 in octants 1 and 2, respectively. Figures 5.8 and 5.9 give the profiles at 8° radius for the same time periods and octants.

The 6° profiles show negative zonal winds for periods R0 through R2 in octant 2 at all levels of the troposphere. In octant 1 the zonal winds are easterly for all but the 150-200 mb levels where they are weakly westerly. By periods R3 and R4 there is very strong westerly flow in both octants throughout most of the depth of the troposphere.

Zonal wind profiles at 8° in octant 1 and octant 2 indicate strong upper tropospheric westerly flow during period R2. Periods R0 and R1 show mostly negative zonal winds. For periods R3 and R4 there is substantial westerly flow through the entire vertical extent of the troposphere.

Summary

Figures 5.6 and 5.7 showed that recurving Typhoon Flo did not begin to recurve until positive zonal winds had penetrated to within 6° of the cyclone's center in octant 2. This

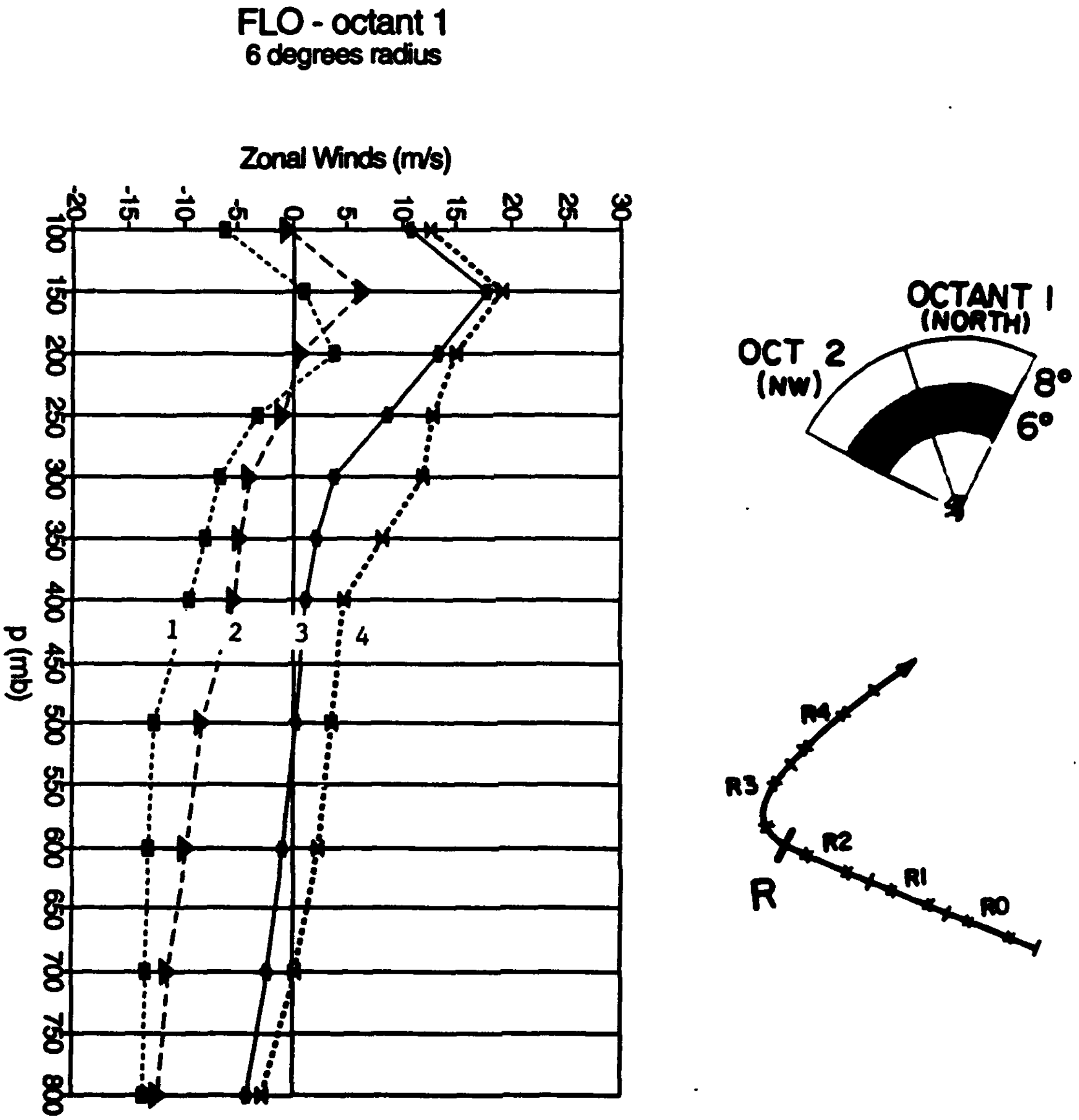


Figure 5.6: Zonal wind vertical profile for Typhoon Flo for periods of R1 through R4 in octant 1 at 6° radius from the cyclone center.

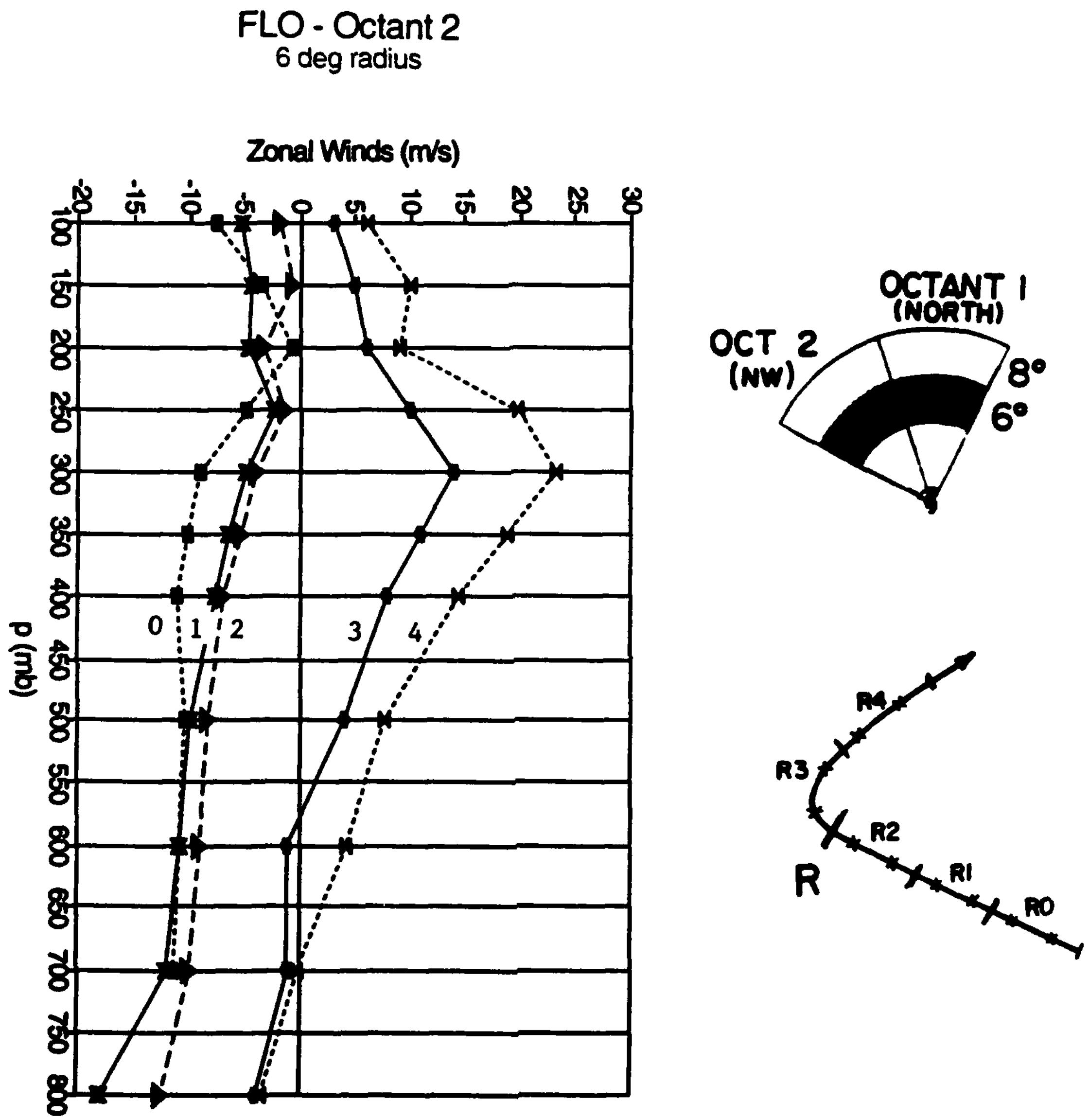


Figure 5.7: Zonal wind vertical profile for recurving Typhoon Flo for periods of R0 through R4 in octant 2 at 6° radius from the cyclone center.

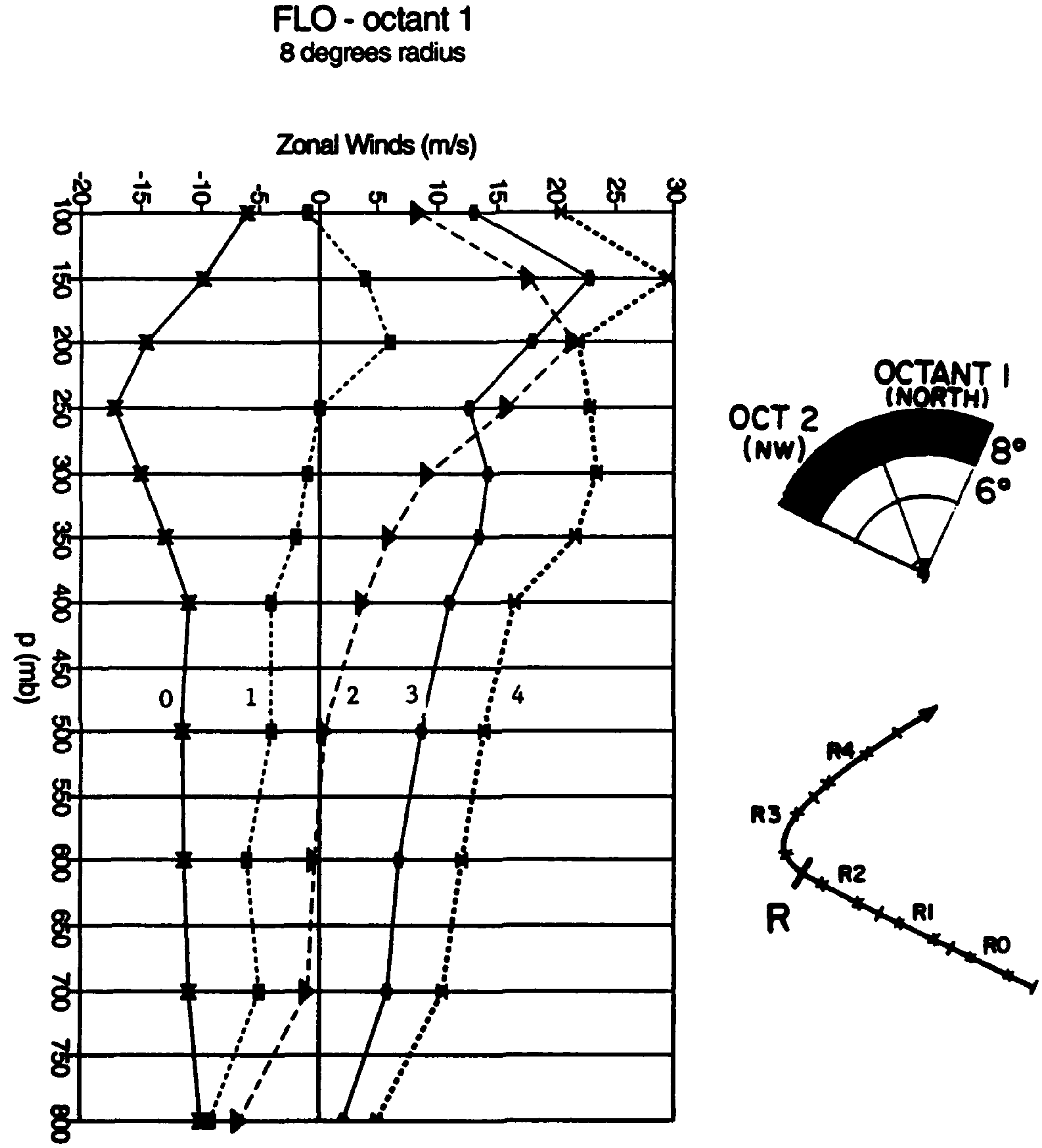


Figure 5.8: Zonal wind vertical profile for recurving Typhoon Flo for periods of R0 through R4 in octant 1 at 8° radius from the cyclone center.

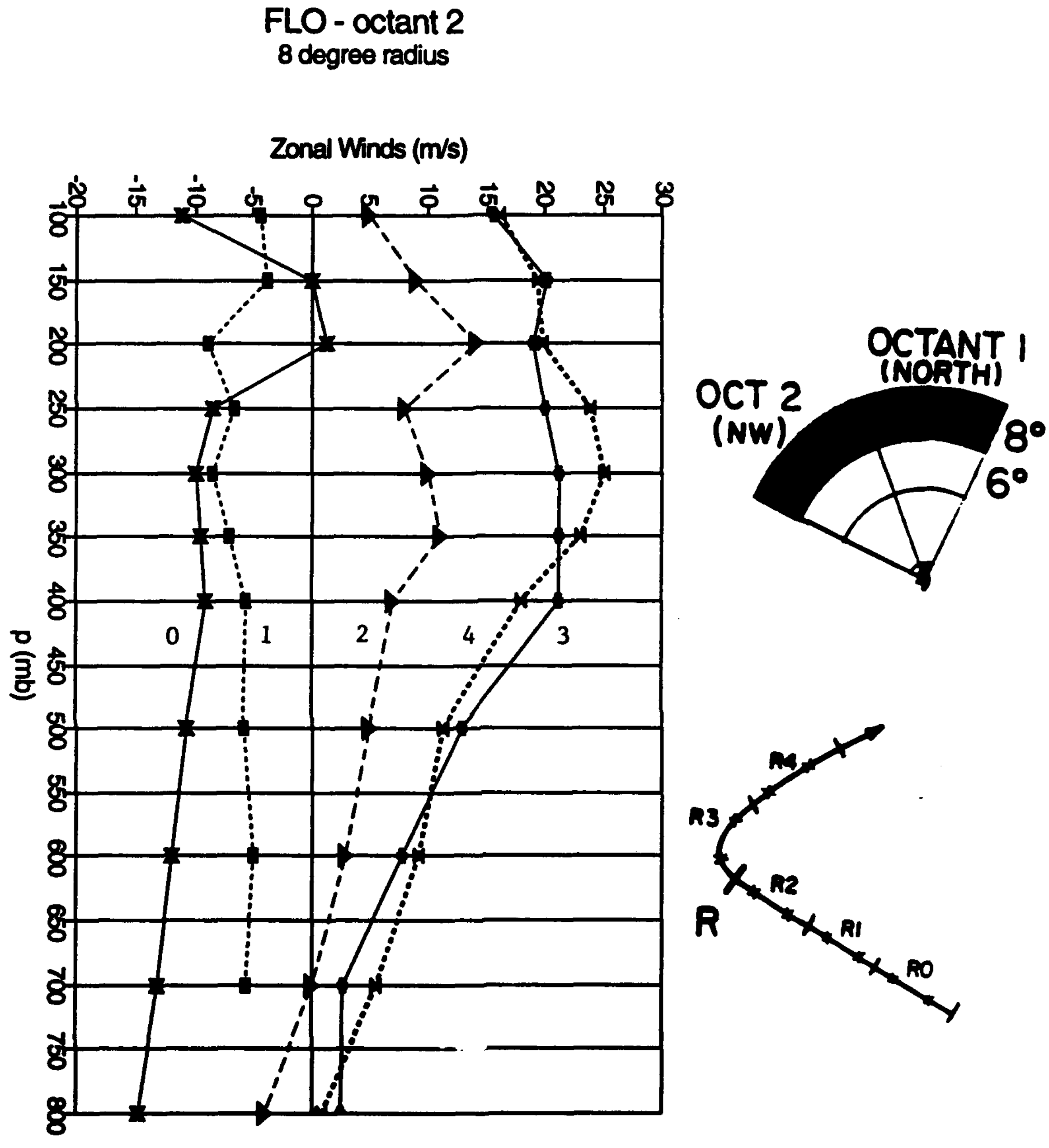


Figure 5.9: Zonal wind vertical profile for Typhoon Flo for periods of R0 through R4 in octant 2 at 8° radius from the cyclone center.

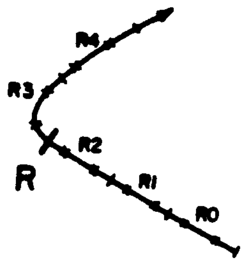
verifies the findings of Hodanish (1991). It is likely that these upper tropospheric zonal winds at 6° radius to the northwest of the cyclone are a crucial factor in determining if a cyclone is actually going to begin recurving or if it remains on a west-northwest course. Zonal wind profiles at 8° showed that significant changes in the environmental wind fields can occur with no immediate effect on the motion of the cyclone. Such changes may signify that the storm is likely to begin recurving within the next 24 hours. But the key to the recurvature is that as Hodanish (1991) found, positive zonal winds must reach to within 6° radius before the cyclone actually begins its initial right turn movement.

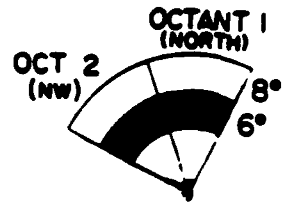
5.5 Satellite Cloud-Drift Wind Results

Figures 5.10 and 5.11 provide satellite derived cloud-track zonal winds for octants 1 and 2 respectively at 200 mb and 6° from the cyclone center. Figures 5.12 and 5.13 show the same information at 8° and 10° radius for octant 1. Figure 5.14 provides an overall look at octant 1 zonal winds at 10°, 8°, and 6° from the cyclone center.

Summary

The cloud track winds at the 200 mb level for Typhoon Flo provide similar results as those found from the rawinsonde composites. Once the zonal winds in octant 2 at 6° radius became westerly during period R3, the cyclone is already in its recurvature process. The 6° radius octant 2 winds during period R2 were weakly easterly. Octant 1 showed increasing westerly flow from period R2 onward. At 8° and 10° radius in octant 1 there were positive zonal winds observed during period R1. These satellite winds agree well with the rawinsonde zonal winds and support the findings of Hodanish (1991).





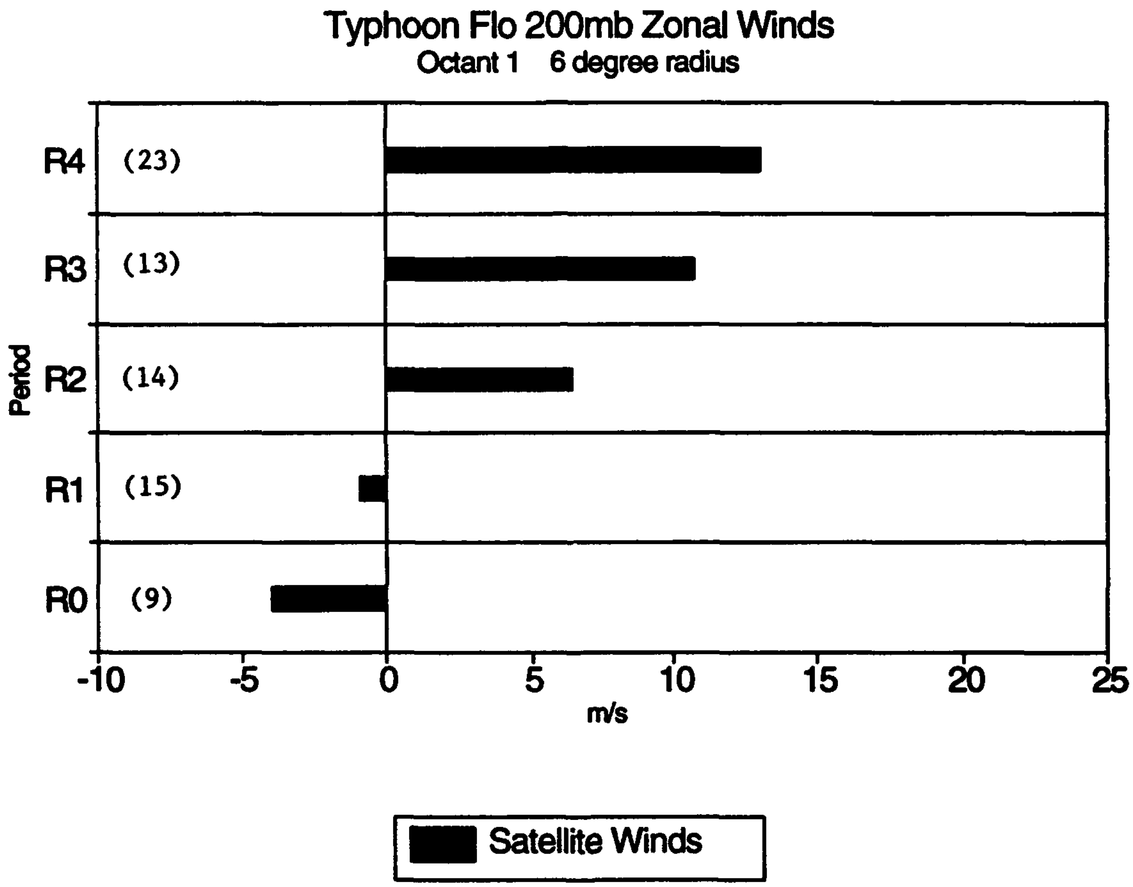


Figure 5.10: Satellite-derived 200 mb zonal winds for Typhoon Flo for periods of R0 through R4 in octant 1 at 6° radius from the cyclone center. The numbers in parentheses indicate the number of observations.

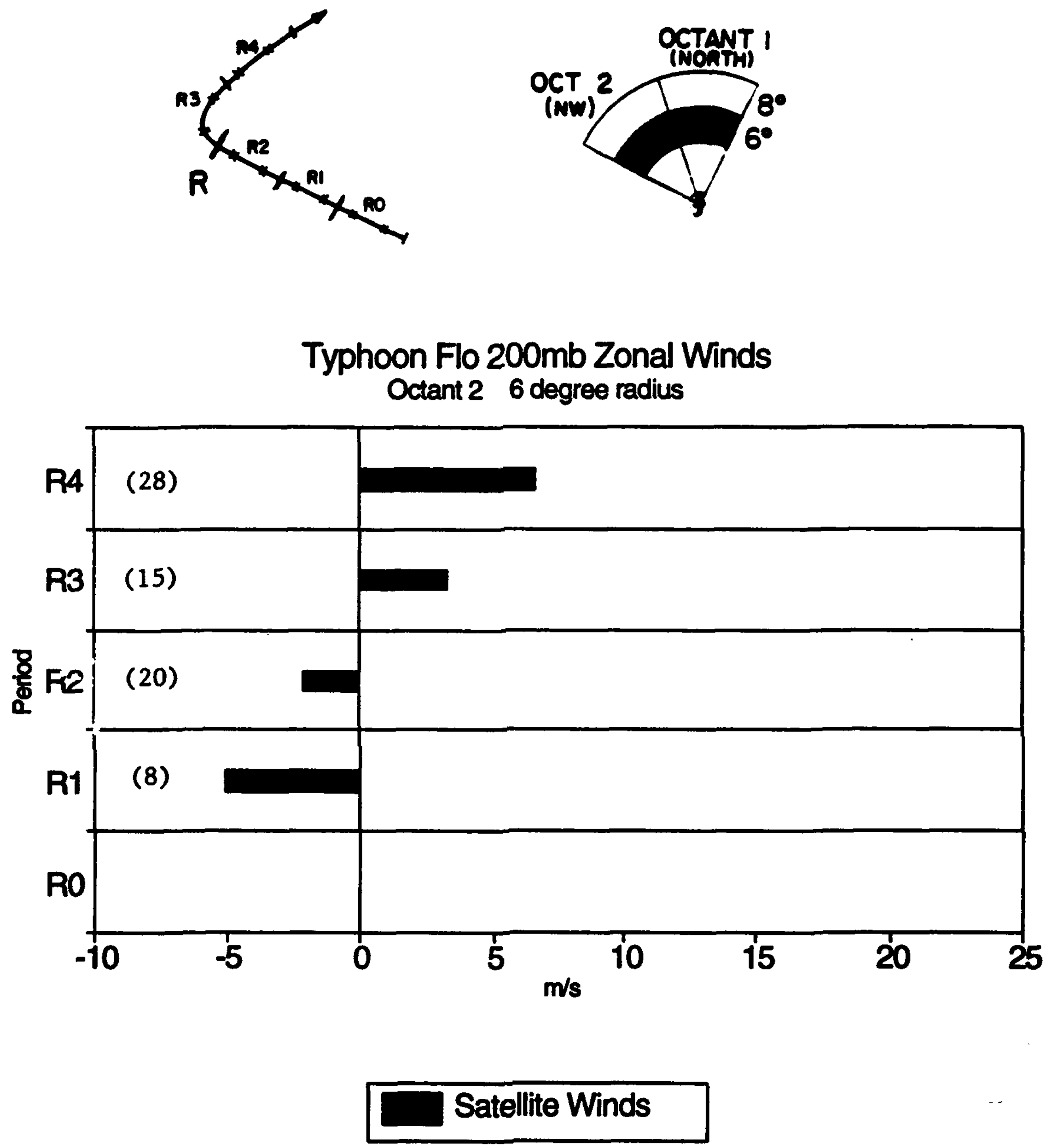


Figure 5.11: Satellite-derived 200 mb zonal winds for Typhoon Flo for periods of R1 through R4 in octant 2 at 6° radius from the center. The numbers in parentheses indicate the number of observations.

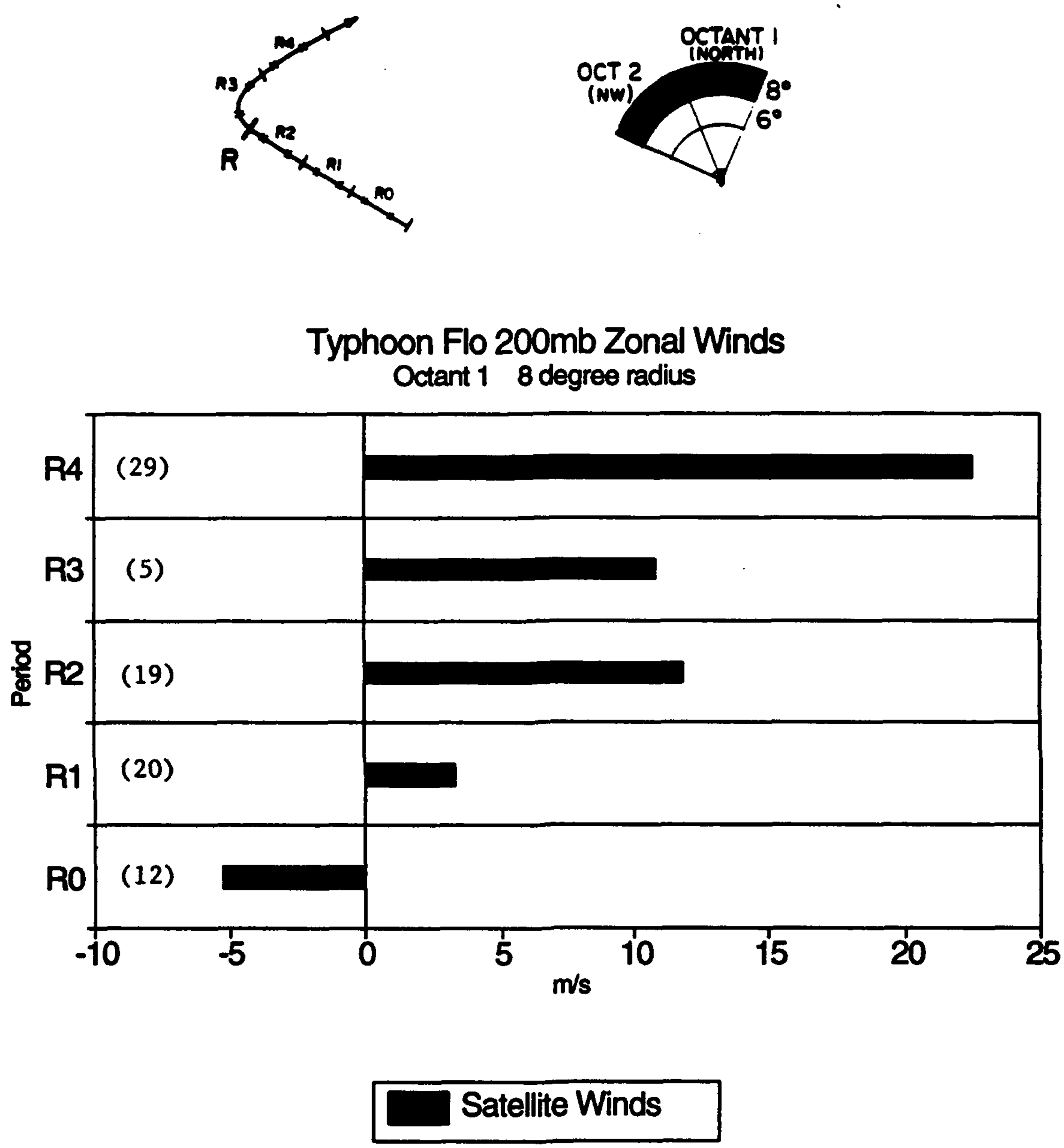
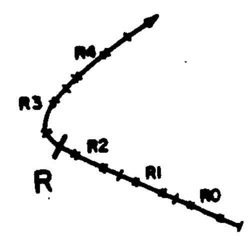
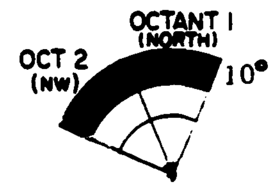


Figure 5.12: Satellite-derived 200 mb zonal winds for Typhoon Flo for periods of R0 through R4 in octant 1 at 8° radius from the cyclone center. The numbers in parentheses indicate the number of observations.





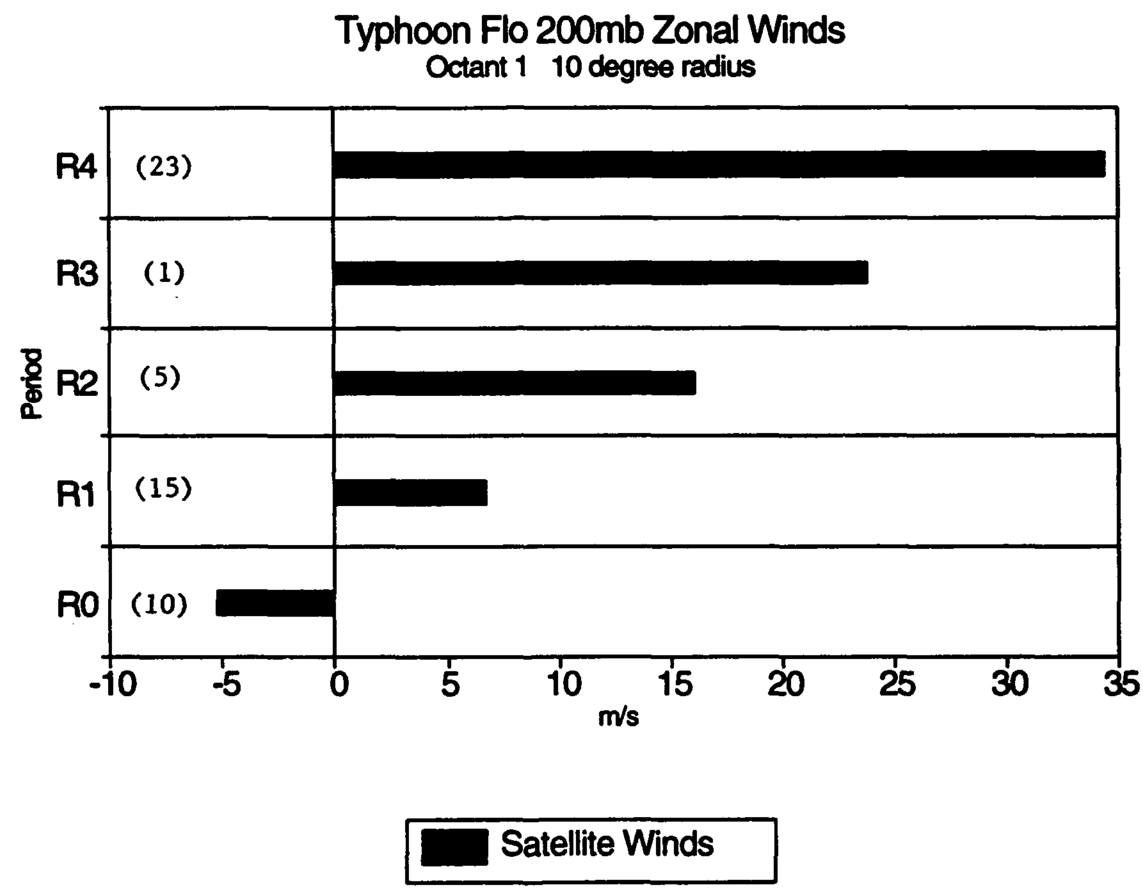


Figure 5.13: Satellite-derived 200 mb zonal winds for Typhoon Flo for periods of R0 through R4 in octant 1 at 10° radius from the cyclone center. The numbers in parentheses indicate the number of observations.

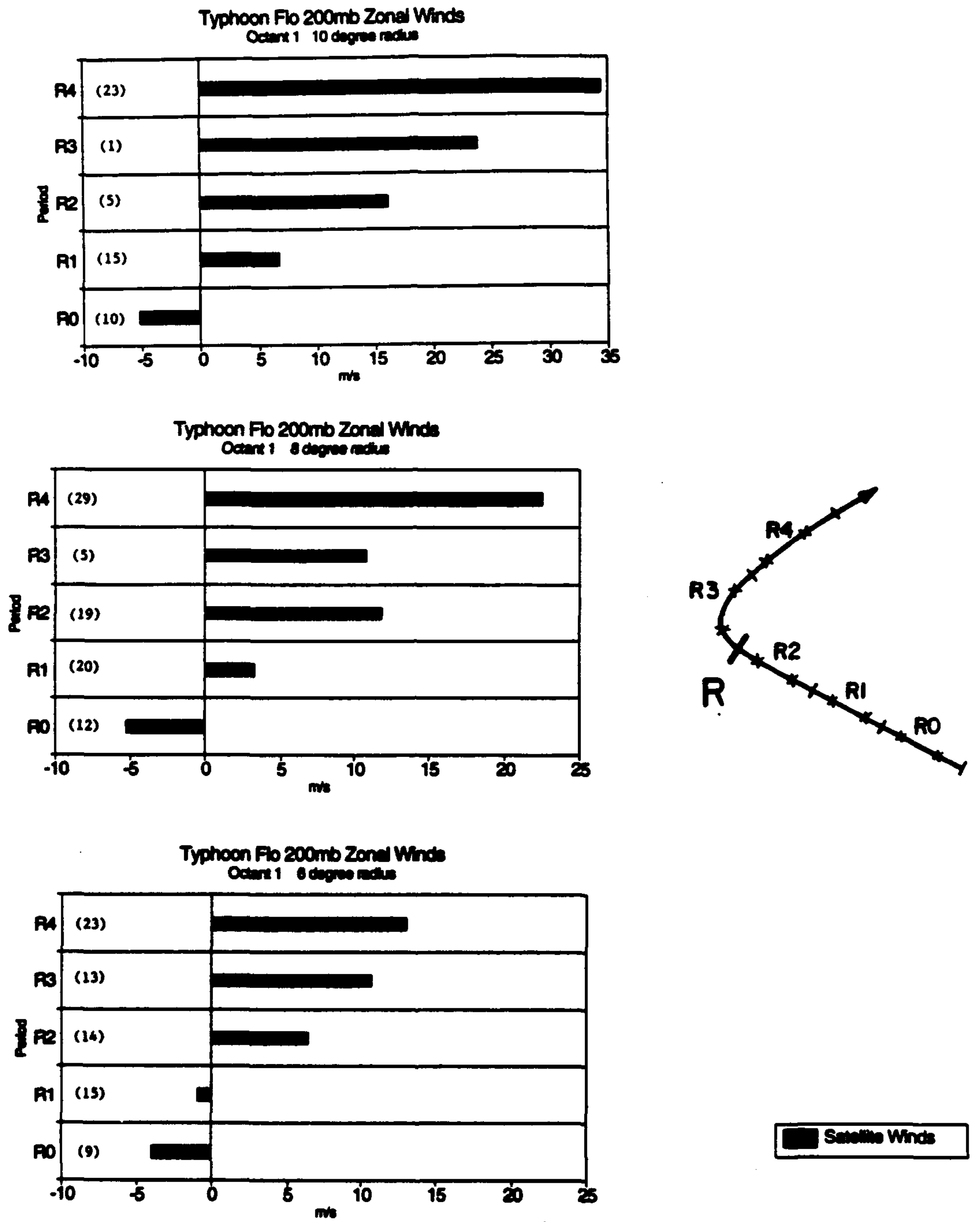


Figure 5.14: Satellite-derived 200 mb zonal winds for Typhoon Flo for periods of R0 through R4 in octant 1 at 10°, 8°, and 6° radius from the cyclone center. The numbers in parentheses indicate the number of observations.

Chapter 6

SUMMARY DISCUSSION

The TCM-90 experiment was specially designed to study tropical cyclone motion. An important feature of this field experiment was to determine if such a rawinsonde network augmentation as was accomplished in the TCM-90 experiment would be able to give improved individual case and time period steering flow information from which track forecast improvements would result. These special observations, particularly the extra ship rawinsonde observations, provided the best opportunity yet to try to measure individual case cyclone steering flow over the open ocean where large atmospheric data inadequacies are always present.

This study found that:

1. Despite the substantial augmentation in the rawinsonde data network which the TCM-90 experiment and the auxillary international programs effected, the number of rawinsonde observations almost always fell short of providing quantitative information sufficient to specify a reliable individual case cyclone steering current. This was also true of the composite analysis of five to ten cases.

2. When all TCM-90 westward moving cyclones were composited together however, quite similar cyclone motion and outer radius steering flow results were obtained. These compared favorably with the much larger 21-year westerly motion composites in the West Pacific and the West Atlantic as discussed by Gray (1991). TCM-90 composite northward and northeastward cases compared reasonably well as regards to direction but not speed. TCM-90 northward and northeast composite motion cases showed consistently slower cyclone motion than did the more extensive composite data analysis of Gray (1991, 1992).

We have not been able to figure out why the speed of the northward and northeastward moving cyclones in TCM-90 were slower than the more extensive rawinsonde composite measurements. It is difficult to ascribe this speed difference to the smaller data sample. It is to be noted that individual case analysis of the synoptic-flow experiments of the HRD of NOAA (see Franklin, 1990; Kaplan and Franklin, 1991; and Marks *et al.*, 1991) have indicated a generally faster motion for the cyclone center compared to the average surrounding steering flow. This is in agreement with the earlier and larger composite analyses.

3. There is a sizable amount of natural variability in the tropical cyclone's surrounding steering flow winds for different cyclones moving in the same approximate direction and speed. It is this surrounding flow natural variability (together with some interior grid positioning variations) which makes accurate steering flow determination in the individual motion cases so difficult. Despite the typical presence of an extra 3-5 rawinsonde reports within 6-8° of a cyclone in the TCM-90 cases (and this is quite an enhancement), a reliable steering current could not be determined. It is for this reason that cyclone extrapolation procedures are usually considered a more reliable way to gage a cyclone's steering current than surrounding wind data.

The results of this study emphasize the difficulty in the measurement of tropical cyclone steering flow over the oceans. Even with the extra observations of a much enhanced special data network such as TCM-90 and the companion programs (TATEX, SPECTRUM) individual case surrounding flow measurements were usually inadequate for a realistic specification of individual case and time period steering. It remains to be seen how much track forecast improvement will be able to be made by the numerical prediction tests with this enhanced data set.

Recurvature. Of all the operational problems involved with tropical cyclones, track forecasting is considered to be of the greatest importance. And of the different track forecasting problems, recurvature is the most important. This research and that of Hodanish (1991) shows that, with regards to cyclone recurvature, there is a special level and special

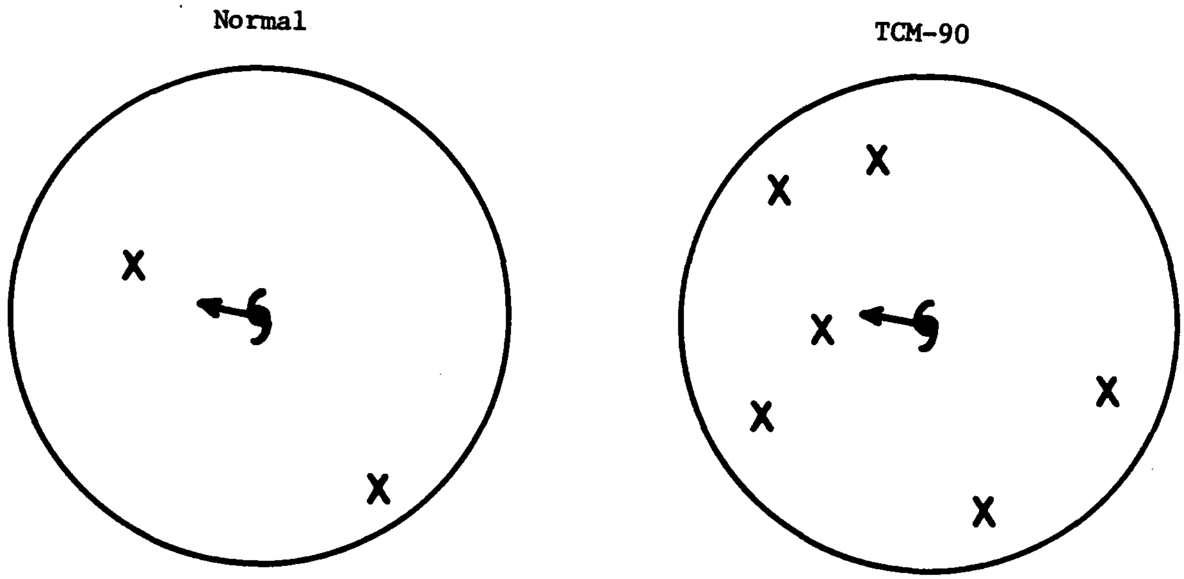


Figure 6.1: Comparison of the typical rawinsonde observational density within 15° radius of a tropical cyclone to that available during the TCM-90 field experiment.

area 6 to 8° radius to the north and northwest of the cyclone which offers a special "window of forecast opportunity" for the forecasting of individual case recurvature up to 24 hours before it begins to take place (see Fig. 6.2). Here the observed wind differences between recurvature and non-recurvature cases are very large, while at other azimuths, radial belts, and levels wind measurement differences between recurving and non-recurving cases are much smaller and typically within the natural turbulent and measurement inconsistencies.

For tropical cyclone recurvature, as with the case of Typhoon Flo, individual case zonal wind values in the upper troposphere ($\sim$ 200 mb) to the north and northwest of the cyclone were observed to be very different ($\sim$ 20 m/s) from the similarly located zonal wind patterns of the non-recurving cases. These large wind differences were much greater than the typical natural and instrumental (S.D. $\sim$ 7-8 m/s) variability inherent in the individual case information at these levels. This special area to the cyclone's north and northwest might be designated as the "window of forecast opportunity". When strong westerly winds penetrated to within 8° radius on the north or northwest side of the tropical cyclone, the beginning of cyclone recurvature is expected to take place in the next 24 hours (Hodanish,

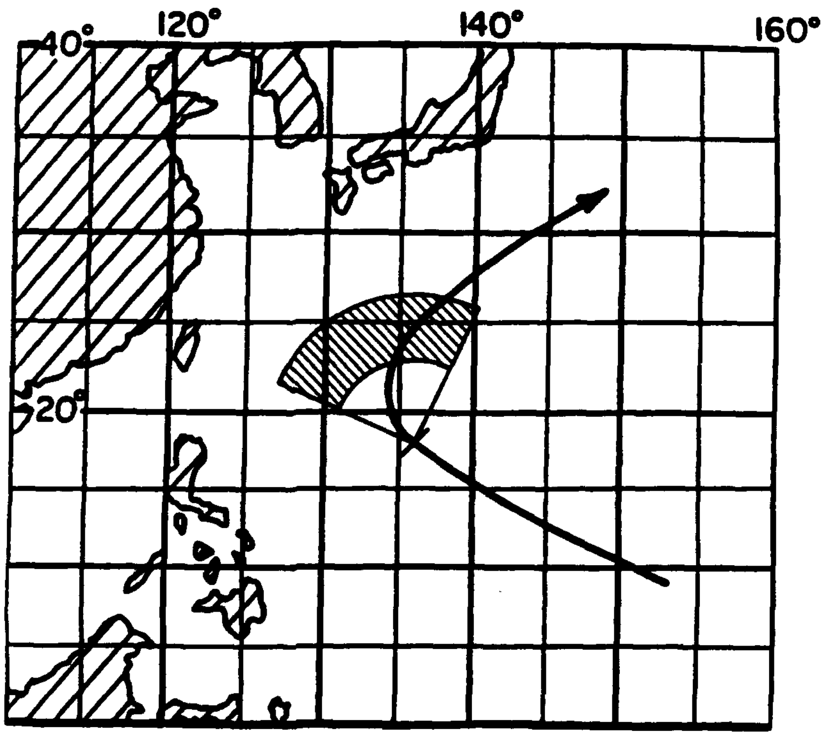


Figure 6.2: Depiction of the critical "window of forecast opportunity" in the upper troposphere where key zonal wind component differences are observed between recurving and non-recurving tropical cyclones.

1991). When westerly winds reach to within 6° radius, then beginning recurvature has just commenced.

The improvement of JTWC 48 and 72-hour forecast skill as reported by Shoemaker *et al.* (1990) from aircraft reconnaissance flights near the 400 mb level and 6-8° to the north and northwest of the Northwest Pacific tropical cyclone (see Fig. 6.3), gives further observational support (see Table 6.1) to the importance of wind data in this special "window of forecast opportunity" region. These JTWC forecast improvements resulted primarily from improvements in the handling of the recurvature situation.

In terms of forecasting future tropical cyclone motion and particularly recurvature, we find that data on the south and east sides of the cyclone offer little or no aid even if this data should be needed to initiate numerical models. It is the data to the north and northwest sides which is usually the crucial factor in future cyclone turning motion determination. Because tropical cyclones are infrequent, it appears that the type of information needed for improved forecasting is not necessarily a denser rawinsonde network which would

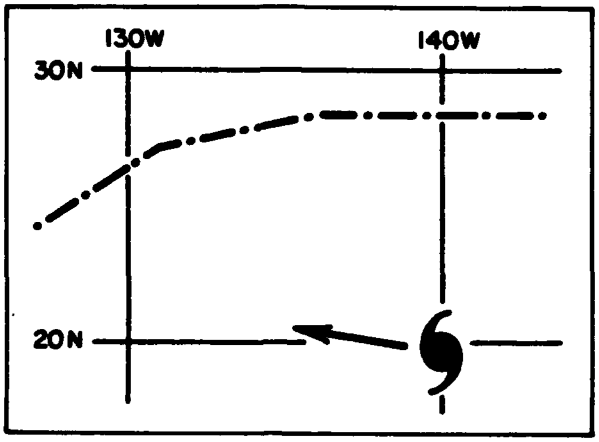


Figure 6.3: Illustration of typical reconnaissance mission (dot-dash line) in relation to current storm position (spiral arms) in the western North pacific. Flights were at 400 mb and observations were made every 111 km. (From Shoemaker *et al.*, 1991).

Table 6.1: Comparison of JTWC TC forecast track errors during 1983-86 for forecasts made in the 6-, 12-, 18-, and 24-h periods following synoptic reconnaissance vs similar forecasts that were made when synoptic reconnaissance data were not available. The number of cases in parentheses. Errors are given in km. (From Shoemaker *et al.*, 1991).

	Forecast period	
Stratification	48 h	72 h
With synoptic tracks	387 (229)	589 (196)
Without synoptic tracks	468 (1291)	732 (924)
Average percentage greater forecast error without synoptic reconnaissance	21%	24%

give enhanced information every day, but rather one should strive to have the ability to selectively sample the occasional tropical cyclone at middle and upper tropospheric level on its' poleward side. If routine rawinsonde and satellite information cannot give the desired information, then it would be very beneficial, in an important forecast situation, that reconnaissance aircraft be deployed to gather such information.

The general discussion of this paper on the inability of the TCM-90 to adequately measure individual time period steering flow should not be interpreted as indicating that additions of smaller amounts of upper level atmospheric information, as can be provided by aircraft or satellite, is not highly beneficial. The aircraft appears to be the most useful tool for such selective and high quality data enhancements.

An important step in this direction appears to have been taken by the synoptic flow experiments by the Hurricane Research Division (HRD) of NOAA which have been directed towards providing denser and more spatially uniform wind fields in individual tropical cyclone cases by deploying Omega dropwindsondes from a flight level of about 400 mb. Lord and Franklin (1987) have described the three-dimensional, nested analysis of these wind fields.

Franklin *et al.* (1991) and Franklin and DeMaria (1992) have discussed the impact of these Omega dropwindsondes on the hurricane track forecasts using the barotropic VICBAR model. Depending upon how the evaluation was made and the frame of reference, it was found that in 12 cases of ODW analysis the 24 to 36 hour track forecasts were estimated to have been improved by about 10-25 percent.

Thus, the general success of the special Pacific reconnaissance missions for track improvement as discussed by Shoemaker *et al.* (1990) and the ODW program in the Atlantic rests with the ability to dictate the most profitable location where the needed wind information is to be collected. This offers advantages over the enhanced but fixed rawinsonde data network of TCM-90. The fixed network frequently cannot supply surrounding cyclone wind information where it gives the best forecast advantage.

When aircraft or large-scale conventional analyses at 500 to 200 mb levels and within 5-9° radius to the north and northwest of the tropical cyclone center are not available or

are considered to be of poor quality, then it may be possible to augment the information of this region through use of upper tropospheric synchronous-satellite cloud-drift winds. It may also be possible, with testing and extra calibration, that practical use may be able to be made with the new satellite sounder systems in this crucial northwest region. It may also prove beneficial to try to use satellite-derived water vapor imagery at levels of 300-400 mb to deduce wind conditions in the important "window of forecast opportunity" region. Dvorak (1984) indicates some success with this approach.

REFERENCES

Anthes, R. A., 1982: Tropical cyclones: Their evolution, structure and effects. *Amer. Meteor. Soc.*, 208 pp.

Brand, S., C. A. Beunafe and H. D. Hamilton, 1981: Comparison of tropical cyclone motion and environmental steering. *Mon. Wea. Rev.*, 109, 908-909.

Chan, J. C. L., W. M. Gray and S. Q. Kidder, 1980: Forecasting tropical cyclone turning motion from surrounding wind and temperature fields. *Mon. Wea. Rev.*, 108, 778-792.

Chan, J. C. L. and W. M. Gray, 1982: On the physical processes responsible for tropical cyclone motion. Atmos. Sci. Research Paper No. 358, Colo. State Univ., Fort Collins, Co, 200 pp.

Chan, J. C. L. and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.*, 110, 1354-1374.

Chan, J. C. L., 1984: An observational study of the physical processes responsible for tropical cyclone motion. *J. Atmos. Sci.*, 41, 1036-1048.

Dvorak, V. F., 1984: Satellite observed upper level moisture patterns associated with tropical cyclone movement. *Postprints, 15th Conf. on Hurricanes and Tropical Meteorology*, AMS, Miami, FL, 163-168.

Elsberry, R. L., 1985: A global view of tropical cyclones, Chapter 4. International Workshop on Tropical Cyclones, WMO, Bangkok, Thailand, 25 November to 7 December, 1985.

Elsberry, R. L., 1990: International experiments to study tropical cyclones in the western North Pacific. *Bull. Amer. Meteor. Soc.*, 71, 1305-1316.

Elsberry, R. L., W. M. Frank, G. J. Holland, J. D. Jarrell and R. L. Southern, 1988: *A global view of tropical cyclones*. Office of Naval Research, Marine Meteorology Program, 185 pp.

Elsberry, R. L., B. C. Diehl, J. C. L. Chan, P. A. Harr, G. J. Holland, M. Lander, T. Neta, and D. Thom, 1990: ONR Tropical cyclone motion research initiative: Field experiment summary. Technical Report NPS-MR-91-001, Naval Postgraduate School, Monterey, CA, 93943, 106 pp.

Elsberry, R. L. and R. F. Abbey, Jr., 1991: Overview of the tropical cyclone motion (TCM-90) field experiment. *Preprints of 19th Conf. Hurricanes and Tropical Meteorology*, AMS, Boston, MA, 02108, 1-6.

Fett, R. W. and S. Brand, 1975: Tropical cyclone movement forecasts based on observations from satellites. *J. Appl. Meteor.*, 14, 452-456.

Frank, W. M., 1977: The structure and energetics of the tropical cyclone, I: Storm structure. *Mon. Wea. Rev.*, 105, 1119-1135.

Franklin, J. L., 1990: Dropwindsonde observations of the environmental flow of Hurricane Josephine (1984): Relationships to vortex motion. *Mon. Wea. Rev.*, 118, 2732-2744.

Franklin, J. L. and M. DrMaria, 1992: The impact of Omega dropwindsonde observations on barotropic hurricane track forecasts. *Mon. Wea. Rev.*, 120, 381-391.

Franklin, J. L., M. DeMaria and C. S. Veldon, 1991: The impact of Omega dropwindsonde and satellite data on hurricane track forecasts using the VICBAR model. *Proc., 19th Conf. Hurricanes and Tropical Meteorology*, Miami, AMS, 87-92.

George, J. E. and W. M. Gray, 1976a: Tropical cyclone motion and surrounding flow parameter relationships. *J. Appl. Meteor.*, 15, 1252-1264.

George, J. E. and W. M. Gray, 1976b: Recurvature and non- recurvature as related to surrounding wind/height fields. *J. Appl. Meteor.*, 16, 43-42.

Gray, W. M. 1981: Recent advances in tropical cyclone research from rawinsonde composite analysis. WMO Programme on Research in Tropical Meteorology, World Meteorological Organization, Geneva, Switzerland, 404 pp.

Gray, W. M. 1987: Recent Colorado State University tropical cyclone research of interest to forecasters. NEPRF Research Paper No. CR 87-10, Monterey, CA.

Gray, W. M., 1991: Tropical cyclone propagation. *Preprints of 19th Conf. Hurricanes and Tropical Meteorology*, AMS, Boston, MA, 02108, 385-390.

Gray, W. M., 1992: Physical factors influencing tropical cyclone propagation. New ONR report in preparation.

Gray, W. M., C. Neumann, T. Tsui, 1991: Assessment of the role of aircraft reconnaissance on tropical cyclone analysis and forecasting. *Bull. Amer. Meteor. Soc.*, Vol. 72, 12, 1867–1883.

Guard, C. P., 1977: Operational application of a tropical cyclone recurvature/non-recurvature study based on 200 mb wind fields. FLEWEACEN Technical Note No. 77-1, U.S. Fleet Weather Central, Guam.

Hodanish, S. J. and W. M. Gray, 1991: An observational analysis of tropical cyclone recurvature. Atmos. Sci. Research Paper No. 480, Colo. State Univ., Fort Collins, CO, 124 pp.

Holland, J. G., 1984: Tropical cyclone motion: A comparison of theory and observation. *J. Atmos. Sci.*, 41, 68-75.

Joint Typhoon Warning Center, 1981-91: Annual Tropical Cyclone Reports 1980-90. U.S. Naval Oceanography Command Center/Joint Typhoon Warning Center, COMNAV-MARIANAS Box 17, FPO San Francisco, 96630.

Kaplan, J. and J. L. Franklin, 1991: The relationship between the motion of tropical storm Florence (1988) and its environmental flow. *Preprints of 19th Conf. Hurricanes and Tropical Meteorology*, AMS, Boston, MA, 02108, 93-97.

Lajoie, F. A., 1976: On the direction of movement of tropical cyclones. *Aust. Meteor. Mag.*, 24, 95-104.

Lord, S. J. and J. L. Franklin, 1987: The environment of Hurricane Debby (1982). Part I: Winds. *Mon. Wea. Rev.*, 115, 2760-2780.

Marks, F. D., Jr., R. A. Houze, Jr. and J. F. Gamache, 1991: Dual-aircraft investigation of the inner core of Hurricane Norbert. Part I: Kinematic structure. Submitted to *J. Atmos. Sci.*.

Merrill R. T., 1988: Characteristics of the upper tropospheric environmental flow around hurricanes. *J. Atmos. Sci.*, 45, 1665- 1677.

Neumann, C. J. and J. M. Pelissier, 1981: Models for the prediction of tropical cyclone motion over the north Atlantic: An operational evaluation. *Mon. Wea. Rev.*, 109, 522-538.

Pike, A. C., 1985: Geopotential heights and thickness as predictors of Atlantic tropical cyclone motion and intensity. *Mon. Wea. Rev.*, 113, 931-939.

Sandgathe, S. A., 1987: Opportunities for tropical cyclone motion research in the northwest Pacific region. Technical Report NPS-63- 87-006, Naval Postgraduate School, Monterey, CA, 36 pp.

Sheets, R. C., 1990: The national hurricane center - past, present, and future. *Weather and Forecasting*, 5, 185-232.

Shoemaker, D. N., W. M. Gray, and J. D. Sheaffer, 1990: Influence of synoptic track aircraft reconnaissance on JTWC tropical cyclone track forecast errors. *Weather and Forecasting*, Vol. 5, 3, 503–507.

Weatherford, C. L. and W. M. Gray, 1988: Typhoon structure as revealed by aircraft reconnaissance. Part I. Data analysis and climatology. *Mon. Wea. Rev.*, 116, 1032-1043.

WMO, 1986: Proceedings of the WMO International Workshop on Tropical Cyclones (IWTC), Bangkok, Thailand, 25 November-5 December, 1985. Tropical Meteorology Programme Report Series, Report No. 21, WMO/TD-No. 83, WMO, Geneva, Switzerland, 152 pp.

Williams, K. T. and W. M. Gray, 1973: Statistical analysis of satellite observed trade wind cloud clusters in the western north Pacific. *Tellus*, 25, 313-336.

Xu, J. and W. M. Gray, 1982: Environmental circulations associated with tropical cyclones experiencing fast, slow and looping motion. Atmos. Sci. Research Paper No. 346, Colo. State Univ., Fort Collins, CO, 111 pp.

Appendix A

TCM–90 CYCLONE TRACKS

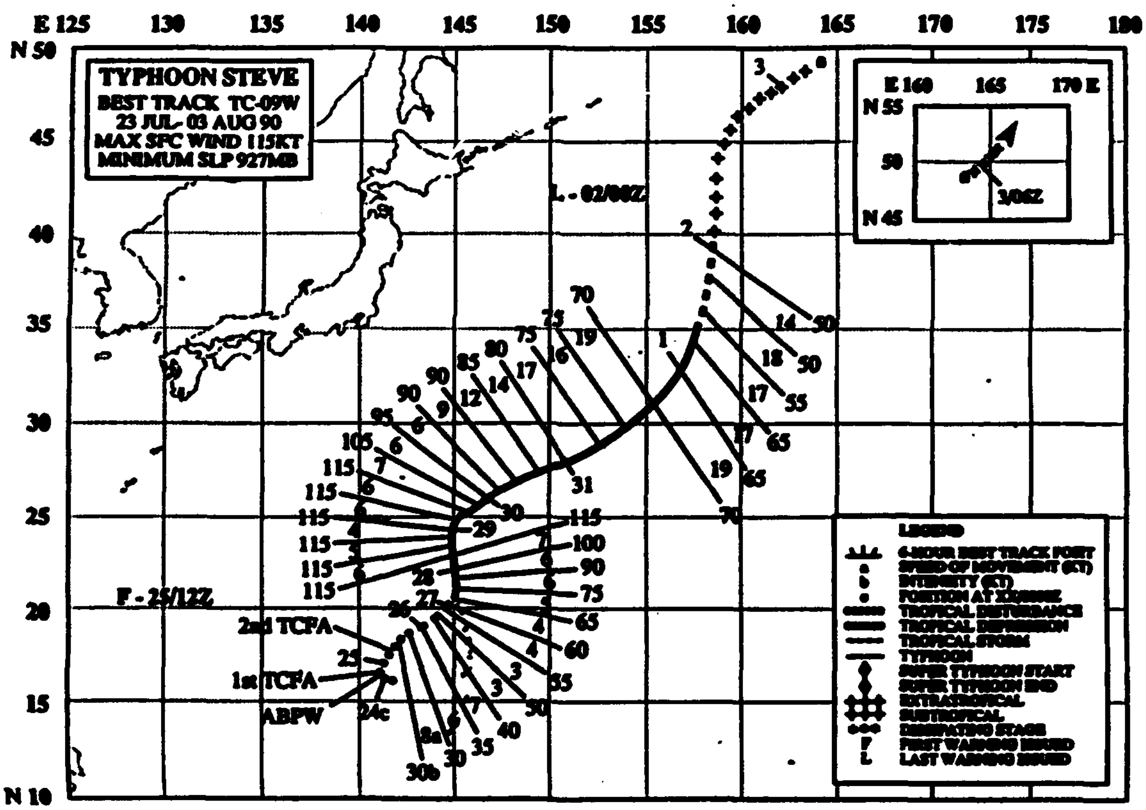


Figure A.1: The best track for one of thirteen tropical cyclones included in this motion study.

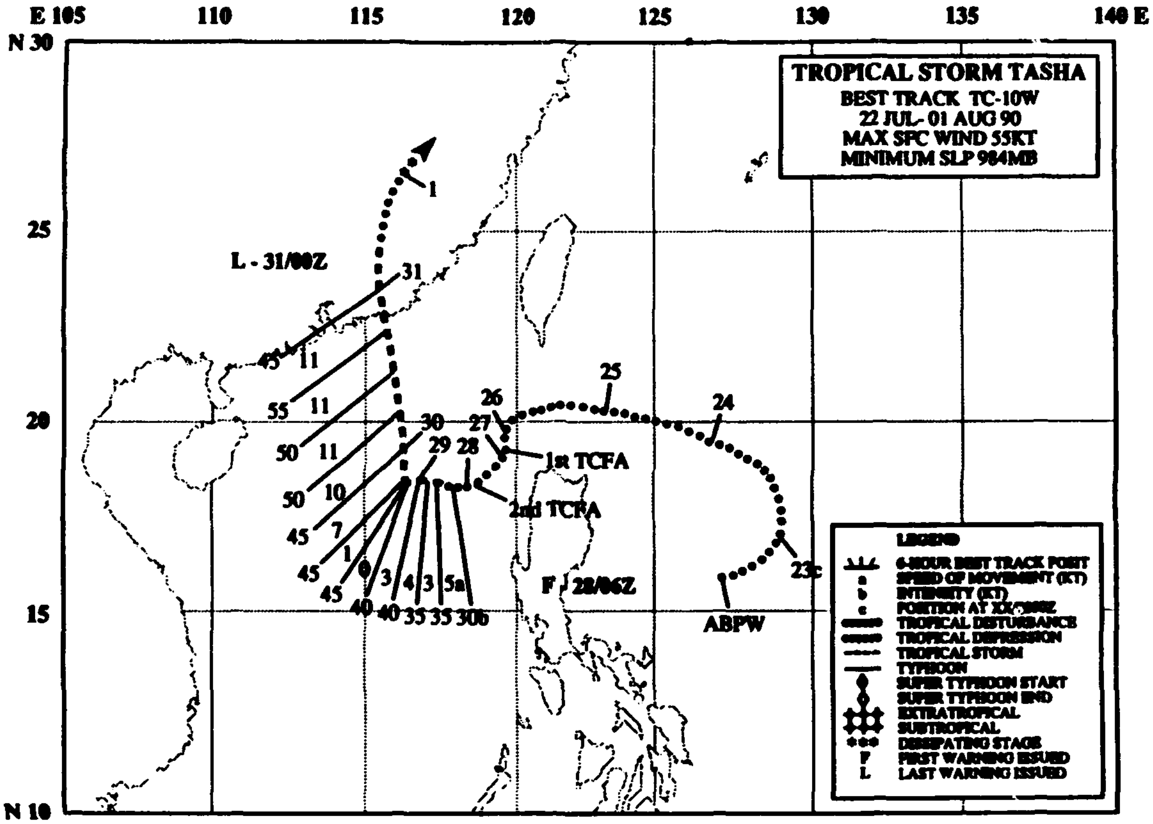


Figure A.2: Same as Fig. A.1.

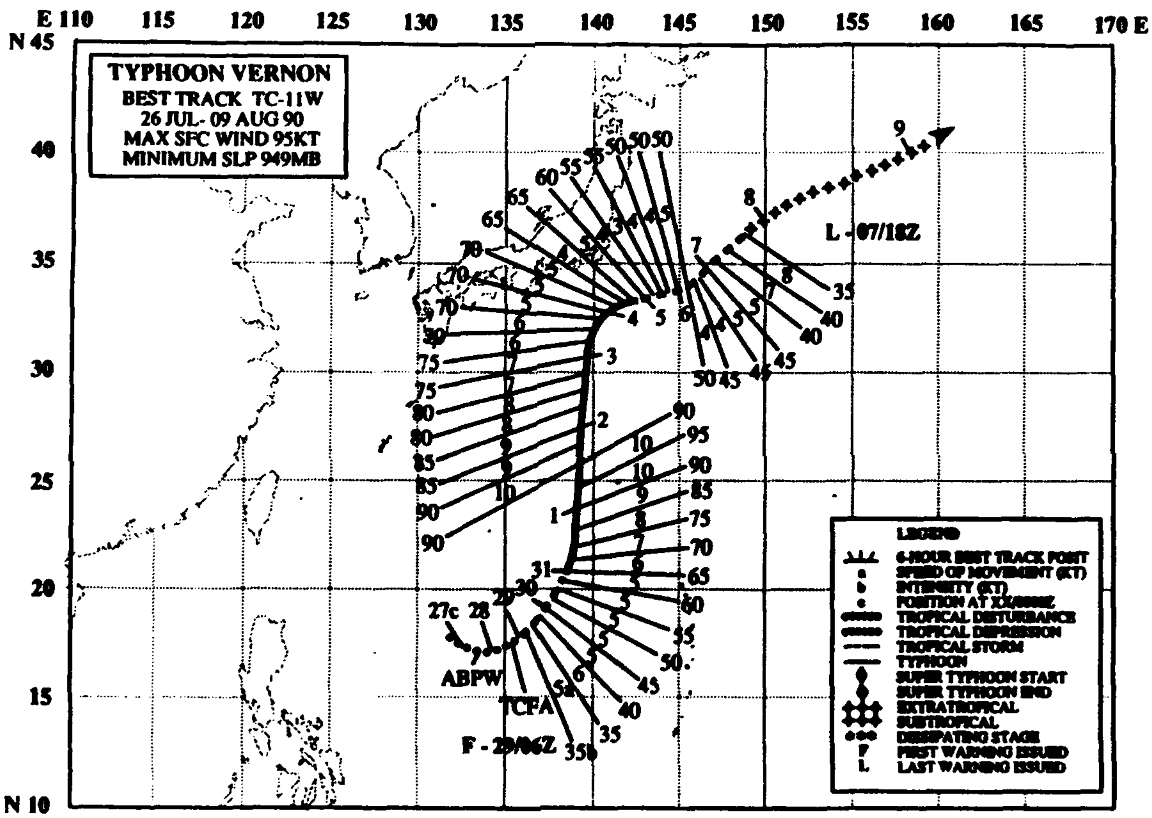


Figure A.3: Same as Fig. A.1.

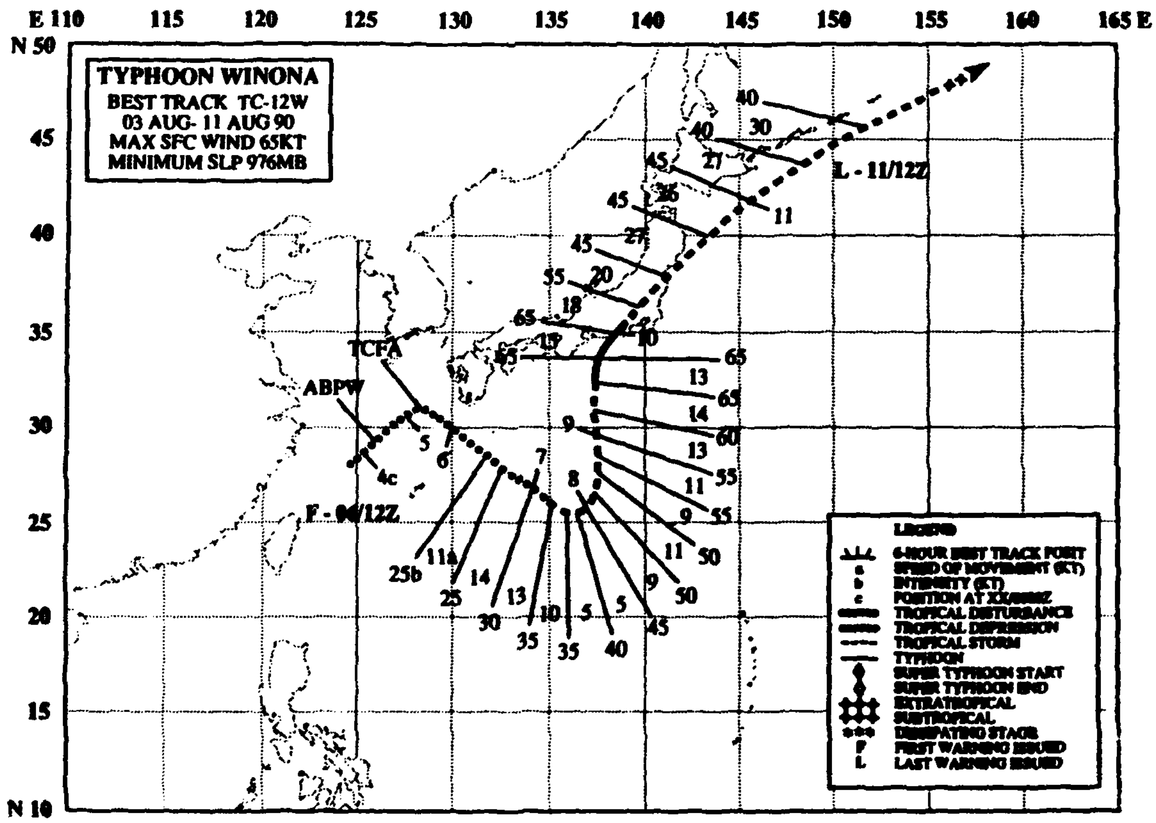


Figure A.4: Same as Fig. A.1.

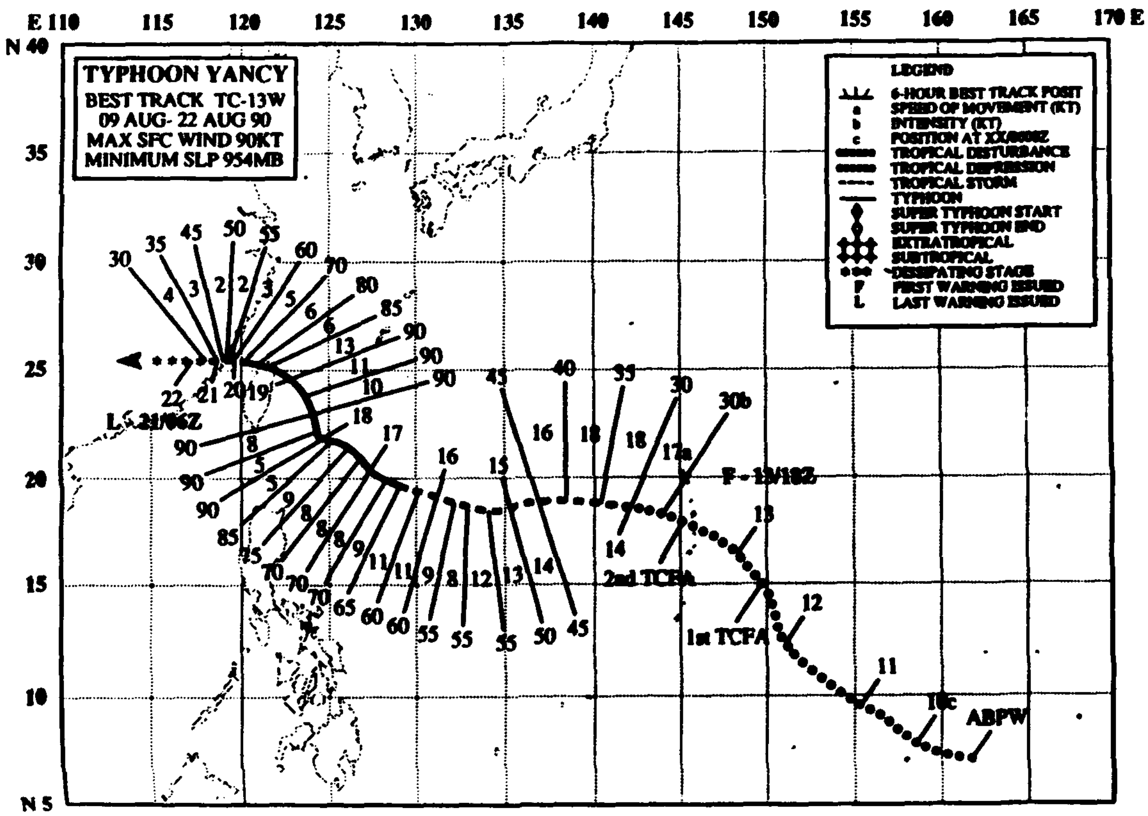


Figure A.5: Same as Fig. A.1.

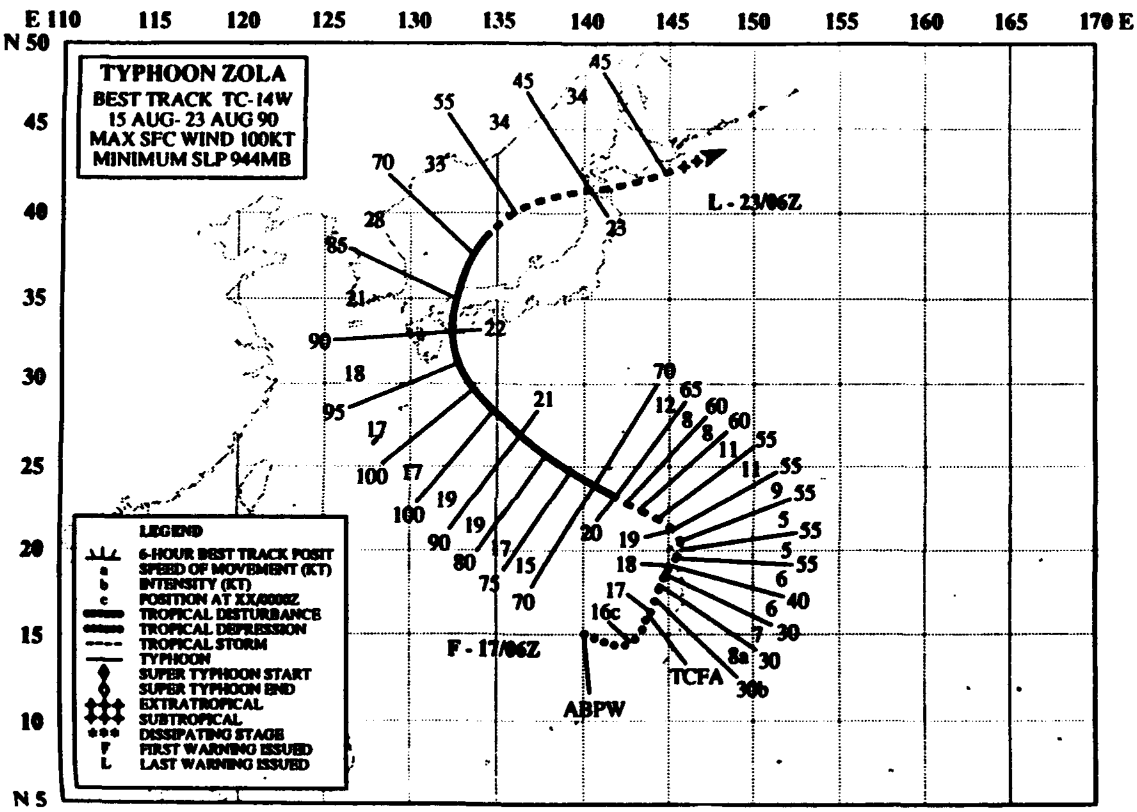


Figure A.6: Same as Fig. A.1.

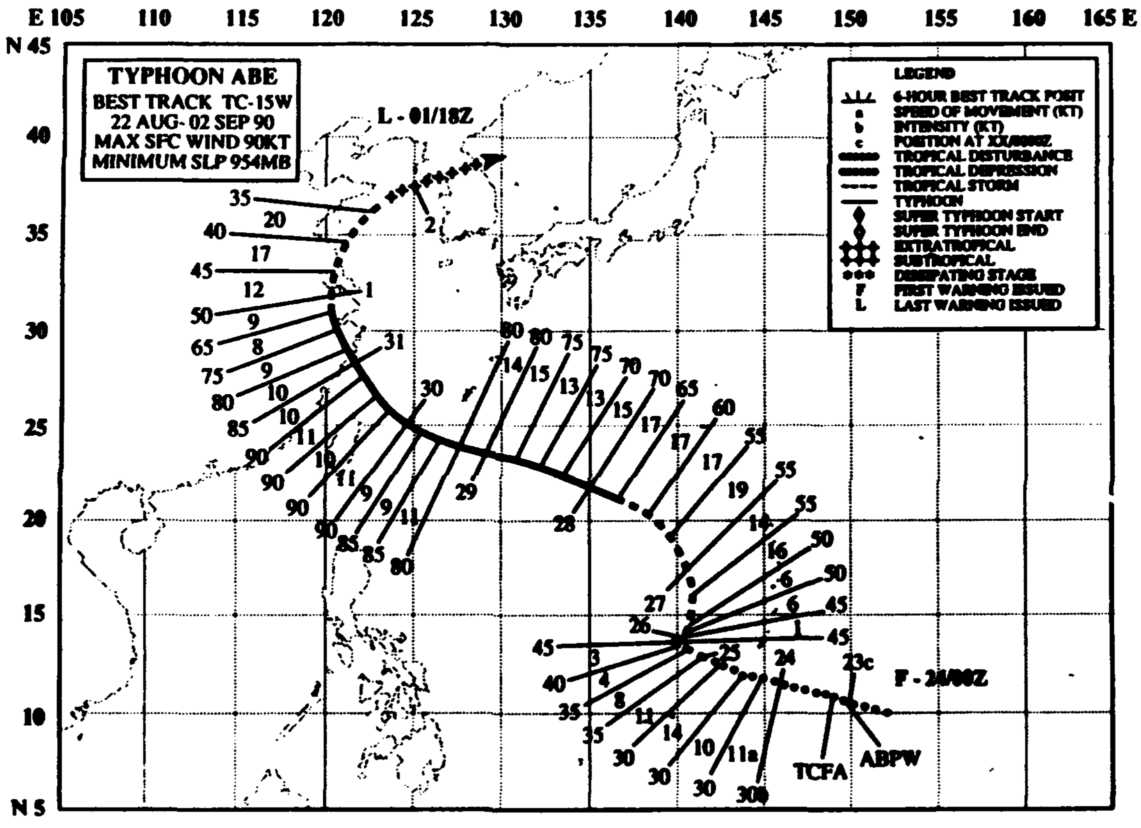


Figure A.7: Same as Fig. A.1.

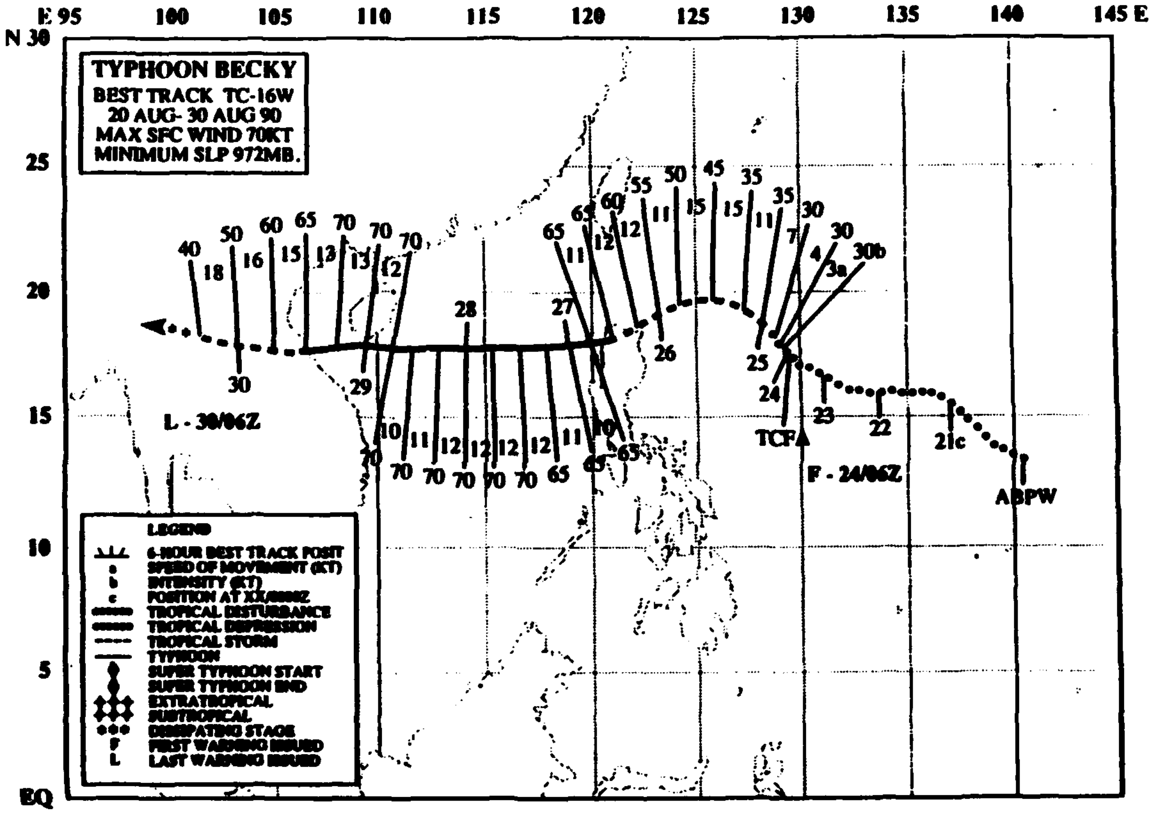


Figure A.8: Same as Fig. A.1.

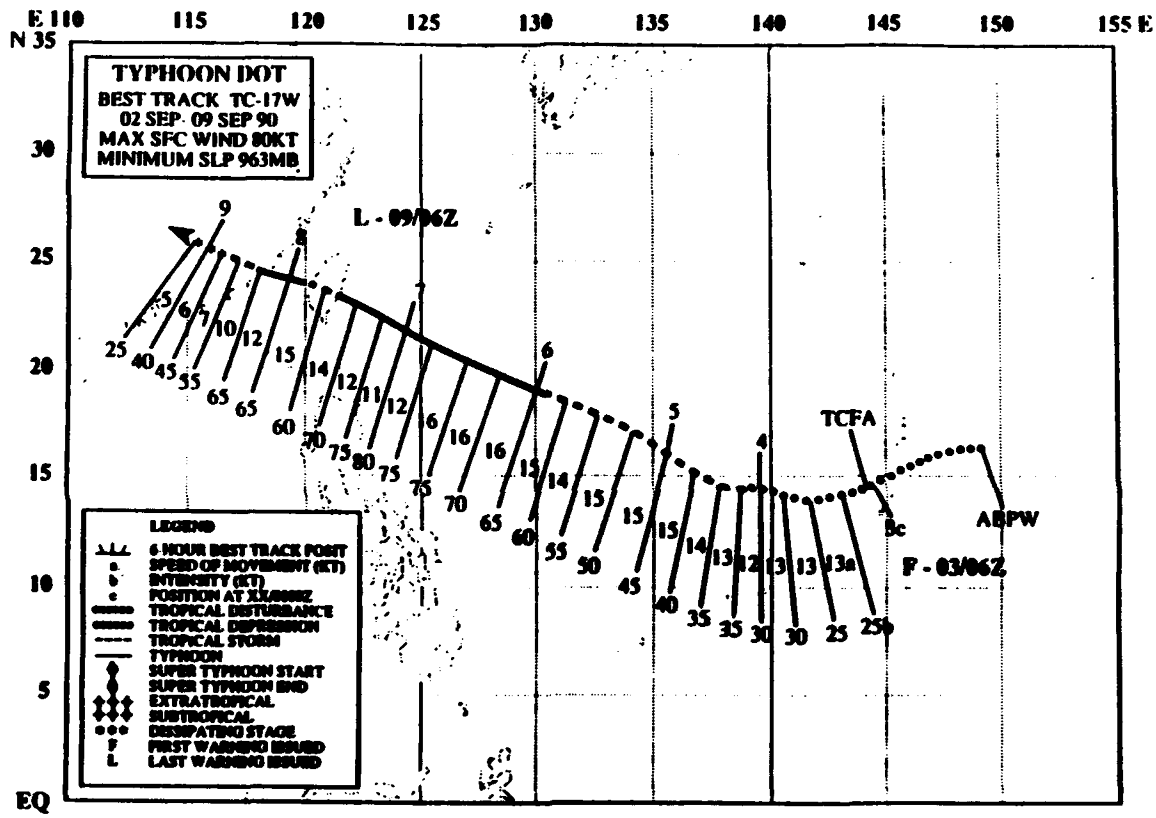


Figure A.9: Same as Fig. A.1.

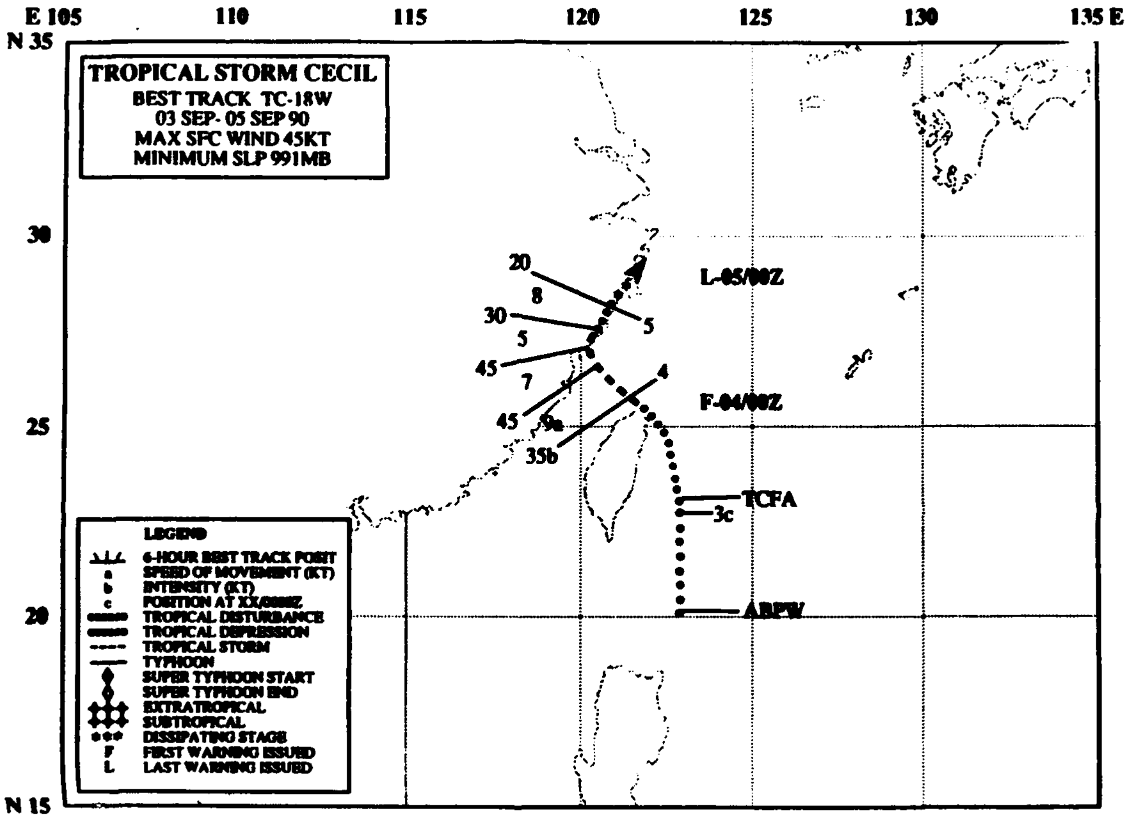


Figure A.10: Same as Fig. A.1.

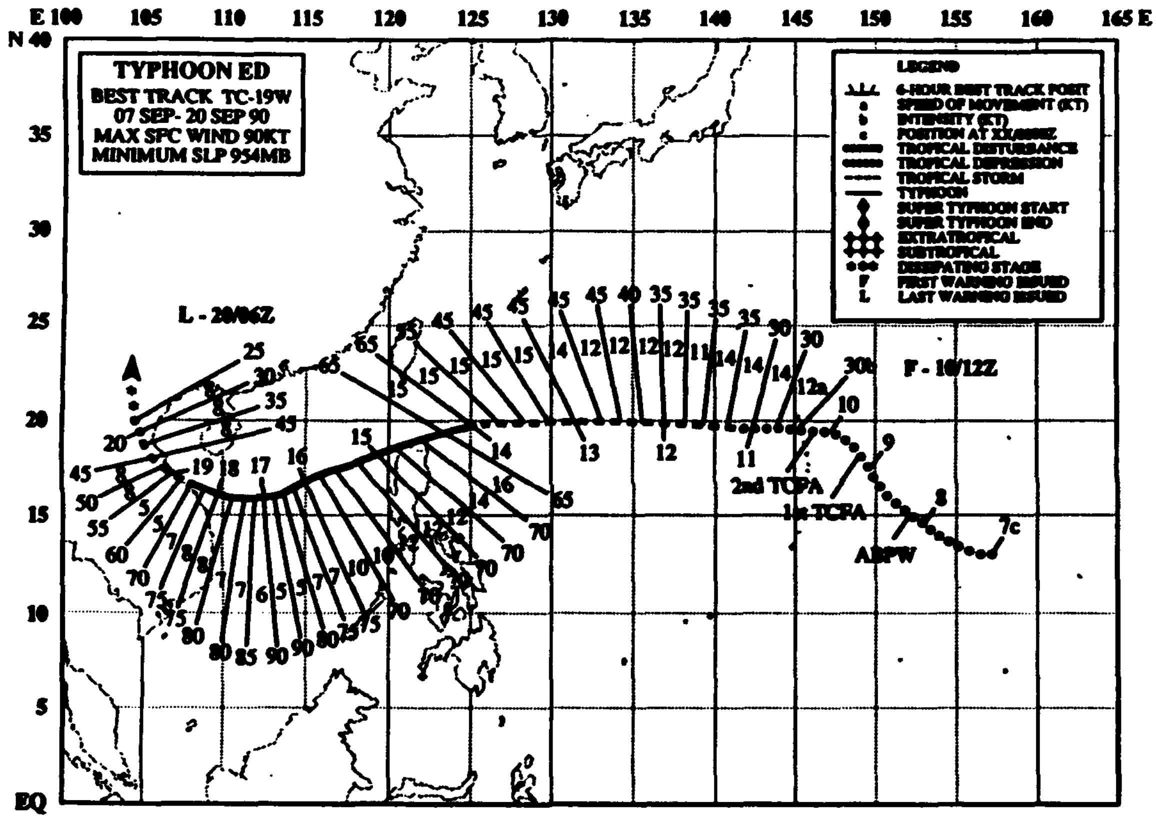


Figure A.11: Same as Fig. A.1.

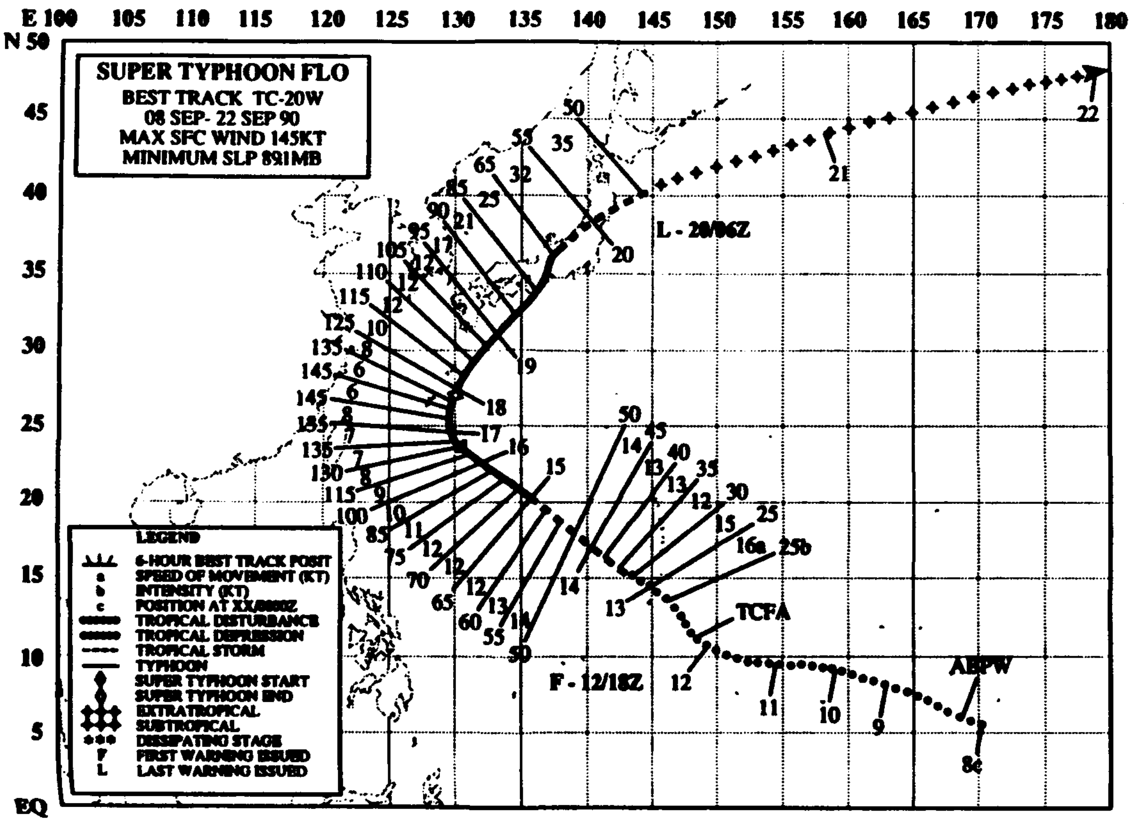


Figure A.12: Same as Fig. A.1.

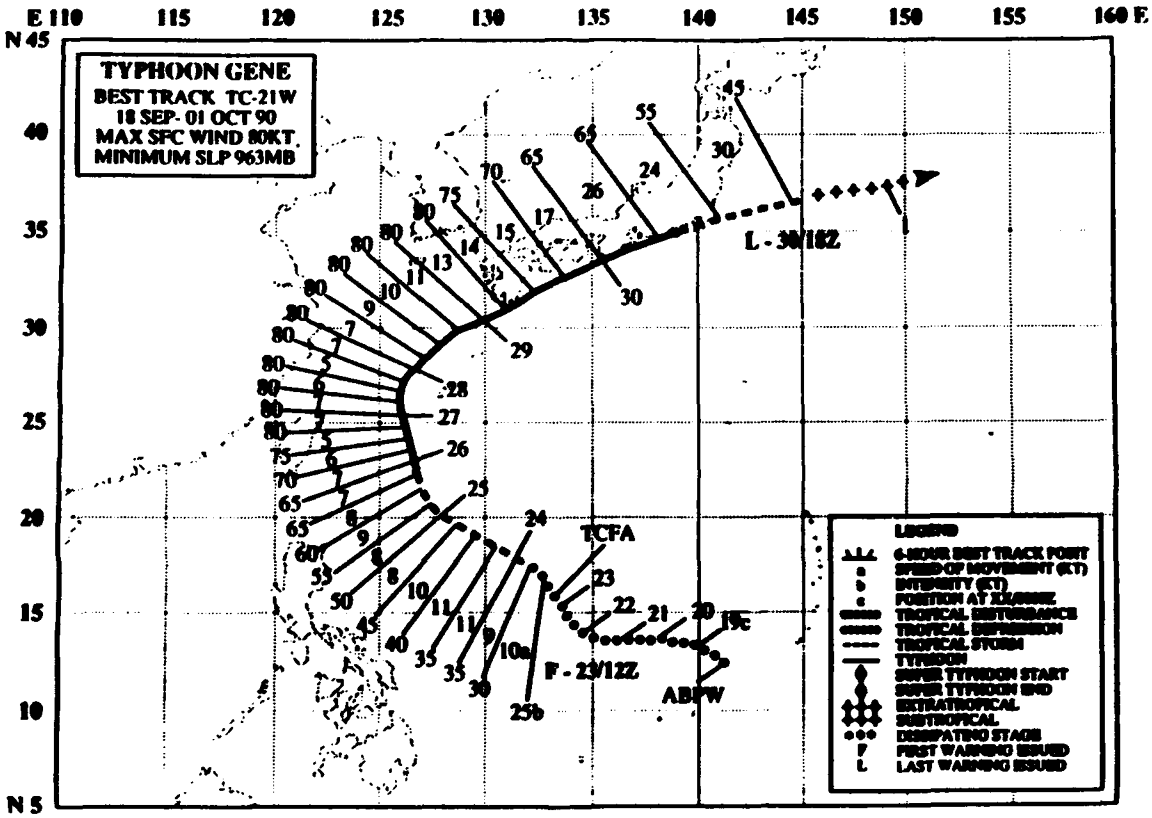


Figure A.13: Same as Fig. A.1.